Generation of Polarization-Entangled Photons by Type-II Quasi-Phase-Matched Waveguide Nonlinear-Optic Device

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***Abstract*—A cross-polarized twin-photon generation device was implemented with Ti-indiffused $LiNbO_3$ waveguides and gratings for Type-II (TE $\rightarrow$ TE + TM) quasi-phase matching. Generation of polarization-entangled twin-photon beams by a simple system using the fabricated device is demonstrated through quantum interference and photon polarization measurement experiment.**

***Index Terms*—Integrated optics, quantum entanglement, quasi-phase matching (QPM), twin photon.**

I. Introduction

THERE has been increasing research interest in quasi-phase-matched (QPM) waveguide nonlinear-optic (NLO) devices for applications to quantum information processing [1]–[6]. An important element for the quantum information technique is twin photons including photons of quantum entangled states, which offer a variety of possibilities in quantum cryptography and quantum teleportation [7]. Generation of polarization entangled photons was demonstrated using two Type-I QPM-NLO devices [5] and using optical fiber loops [8], [9]. The authors have been working on waveguide QPM-NLO twin-photon generation devices [10]–[13]. Recently, we demonstrated implementation of a waveguide cross-polarized twin-photon generation device based upon the Type-II QPM[13]. This device enables generation of polarization entangled photons in an optical system simpler than that using two Type-I QPM devices [5] and potentially compact in comparison to the fiber systems [8], [9]. In this letter, we demonstrate generation of polarization entangled photons in the telecom band by a Type-II QPM waveguide NLO device, and report the results of quantum interference experiments.

II. Device Fabrication and Basic Characteristics

The Type-II QPM device [13] consists of a Ti-indiffused waveguide and a ferroelectric domain-inverted grating for QPM in a z-cut $LiNbO_3$ crystal. Twin-photon generation is based on parametric fluorescence due to the NLO tensor element $d_{24}(= d_{31})$, and the phase matching is accomplished by the Type-II (TE $\rightarrow$ TE + TM) QPM. Devices of interaction length $L = 30$ mm and QPM periods $\Lambda \sim 9.3$ μm were fabricated for generation of twin photons in the 1.55-μm band. Ti film stripe of 100-nm thickness and 7.0-μm width, on the $-z$ surface of a $LiNbO_3$ crystal, was indiffused by heat treatment to obtain single-mode waveguides. Then the QPM structure was fabricated by removing the unwanted domain-inverted layer on the $+z$ surface, uniform domain inversion, and applying a voltage pulse through a periodic electrode to form a domain-inverted grating.

The basic characteristics were examined by using a tunable AlGaAs laser as a pump source. The pump TE mode was excited by end-fire coupling, and the transmitted pump wave was cut by color-glass and interference filters. The dependence of the twin-photon wavelengths upon the pump wavelength was in good agreement with the prediction calculated by using indexes of bulk crystal. To avoid the drift of the wavelength-degenerate point due to photorefractive damage, the experiments were carried out with device temperature kept at 90 ± 0.1°C. At this temperature, the wavelength-degenerate twin photons of $\lambda_1 = \lambda_2 = 1559.8$ nm were generated in a device of period $\Lambda = 9.3$ μm pumped at wavelength $\lambda_3 = 779.9$ nm.

The measured wavelength bandwidths [full-width at half-maximum (FWHM)] of the degenerate twin photons were consistent with the theoretical prediction of 1.0 nm for both polarizations. The output powers P_1, P_2 of the twin beams separated by a polarization beam splitter, were measured using InGaAs PIN photodiodes and a lock-in amplifier, and the pump power P_3 was measured at the waveguide output end. The twin-photon generation efficiency was $P_1/P_3 = 1.9 \times 10^{-10}$ and $P_2/P_3 = 2.3 \times 10^{-10}$ for TE and TM photons, which were of the same order of magnitude as $P_1/P_3 = P_2/P_3 = 5.3 \times 10^{-10}$, predicted [10] by using the coupling coefficient $\kappa_3 = 0.12$ $W^{-1/2}cm^{-1}$ determined from the result of a Type-II QPM second-harmonic generation (SHG) measurement. The twin-photon generation efficiency is orders of magnitude lower then that of Type-I waveguide QPM devices [1], [2], [5], [12], but is not much lower than that of the reported value for optical fiber loops [8], [9].

The correlation of the generated twin photons was examined by separating with a (power) beam splitter (BS) the QPM device output into two beams, detecting them by two single-photon detectors (SPDs) using Giger-mode InGaAs–InP avalanche photodiodes (quantum efficiency ~10%, dark counts ~100 cps), and analyzing the detection signal by using a time interval analyzer (TIA). The obtained histogram of the coincidence counting rate (CCR) dependent on the delay time is shown in Fig. 1. The result clearly indicates the photon correlation peak at zero delay with the resolution ~1 ns reflecting the jitter of the SPD and the TIA.

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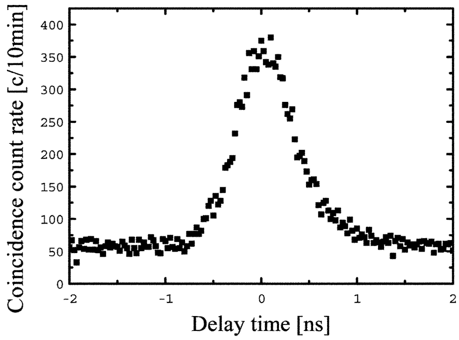

Fig. 1. Correlation of the cross-polarized twin photons.

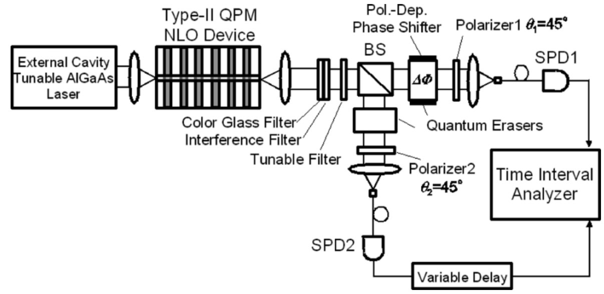

Fig. 2. Setup for polarization entangled state generation and measurement.

III. Generation of Polarization Entangled States

The wavelength-degenerate twin-photon beams generated by the Type-II QPM NLO device can readily be converted into polarization-entangled twin photons by splitting the output beam into two beams by using a BS.

In the single-mode-pair model, the quantum state of the QPM device output may simply be represented by $|H, V\rangle$ denoting the state of twin photons consisting of a horizontally (H) polarized photon and a vertically (V) polarized photon [8], [9]. Consider a BS of a polarization-independent power splitting ratio of 1 : 1. The amplitude operators for the horizontal (x) and vertical (y) components of the fields in the output ports 1 and 2, a_{1x}, a_{2x}, a_{1y}, a_{2y}, can be correlated with those for the input ports 1 and 2, $a_{\mathrm{in}1x}$, $a_{\mathrm{in}2x}$, $a_{\mathrm{in}1y}$, $a_{\mathrm{in}2y}$, by

$$a_{1x} = \sqrt{\frac{1}{2}}(a_{\mathrm{in}1x} + ia_{\mathrm{in}2x}), \quad a_{2x} = \sqrt{\frac{1}{2}}(ia_{\mathrm{in}1x} + a_{\mathrm{in}2x}) \tag{1a}$$

$$a_{1y} = \sqrt{\frac{1}{2}}(a_{\mathrm{in}1y} - ia_{\mathrm{in}2y}), \quad a_{2y} = \sqrt{\frac{1}{2}}(-ia_{\mathrm{in}1y} + a_{\mathrm{in}2y}). \tag{1b}$$

The state generated by the QPM-NLO device and fed into the BS input port 1 can be written as $|\psi\rangle = |H, V\rangle = a^{\dagger}_{\mathrm{in}1x}a^{\dagger}_{\mathrm{in}1y}|0\rangle$. Therefore, the state in the BS output ports is

$$\begin{aligned}|\psi\rangle &= (1/2)\,(a^{\dagger}_{1x} + ia^{\dagger}_{2x})(a^{\dagger}_{1y} - ia^{\dagger}_{2y})|0\rangle \\ &= (1/2)\,\{|xy;0\rangle - i|x;y\rangle + i|y;x\rangle + |0;xy\rangle\}\end{aligned} \tag{2}$$

where $|0\rangle$ denotes the vacuum state. The states where the cross-polarized twin photon appears together in output ports 1 or 2, $|xy;0\rangle$ and $|0;xy\rangle$, can be omitted since they do not affect the photon coincidence counting. After renormalization, we have

$$|\psi\rangle = \sqrt{1/2}\{|H;V\rangle - |V;H\rangle\} \tag{3}$$

where $|H;V\rangle = |x;y\rangle$ denotes the state where a H-$(x$-) polarized photon appears in output port 1 and a V-$(y$-) polarized photon appears in output port 2. If a polarization-selective phase shifter, which gives a differential phase shift $\Delta\Phi$ to the V component only, is inserted in the output port 1, the output state is given by

$$|\psi\rangle = \sqrt{1/2}\{|H;V\rangle - \exp(i\Delta\Phi)|V;H\rangle\}. \tag{4}$$

Thus the two of the four maximally entangled Bell states, $|\psi^{+}\rangle$ and $|\psi^{-}\rangle$, which are not obtained with Type I device, can be generated by setting as $\Delta\Phi = \pi$ and 0, respectively. The time lag between the V and H photons due to the transit time difference in the waveguide device can be compensated for by inserting a $\mathrm{LiNbO_3}$ crystal (quantum eraser) of a length $L/2$, half the QPM-NLO device length, with the crystallographic orientation 90° rotated with respect to that of the device [10], [14].

Generation of the entangled states can be examined by a photon coincidence counting experiment with 45° polarizers inserted in the two output ports of the BS (see Fig. 2). Let XY be coordinate axes rotated 45° with respect to the xy axes for each output port. Then, using the relation between the amplitude operators for the x and y components, and X and Y components, we can rewrite (4) into an expression in XY basis. Omitting the terms which do not affect the coincidence detection, we obtain an expression for the terms which give rise to the coincidence detection through the 45° polarizers

$$|\psi\rangle = (1/2)^{3/2}\,\{1 - \exp(i\Delta\Phi)\}|X;X\rangle. \tag{5}$$

Therefore, when $\Delta\Phi$ is changed, intensity interference of the photons, characterized by the modulation of the CCR in proportion to $|1 - \exp(i\Delta\Phi)|^2$, is observed.

Fig. 2 shows the experimental setup for the entangled state generation and the photon intensity interference measurement. The output of the QPM-NLO device was split into two beams by a BS. Filters were inserted to cut the pump wave, and a tunable filter of 0.9-nm FWHM bandwidth was inserted. As the quantum erasers, $\mathrm{LiNbO_3}$ crystals of a length of $L/2 = 15$ mm were inserted with 90°-rotated orientation. Planar electrodes were attached to the z faces of one of the crystals, and dc voltage was applied to use the crystal also as an electrooptic polarization-dependent phase shifter for giving $\Delta\Phi$. The half wavelength voltage was $V_{\pi} = 2.7$ kV. Photon coincidence counting was performed thorough 45° polarizers for BS outputs by using two SPDs and a TIA. The pump wavelength was carefully adjusted to the wavelength-degenerate point, by monitoring the dependence of the photon counts on the filter tuning.

Fig. 3 shows the measured CCR (time window of 2 ns) dependent on the phase shifter voltage. The accidental CCR (ACCR) was subtracted from the CCR. (ACCR was measured at each phase settings, but was constant $<10\%$ of maximum CCR. The origin of ACCR was dark counts and broad-spectrum fluorescence of the pumped Ti : $\mathrm{LiNbO_3}$ waveguide [13] leaking through filters.) Clear periodic modulation in the CCR with a period of 5.4 kV $(= 2V_{\pi})$, consistent with the theoretical prediction, was observed. The obtained modulation visibility was $V = 0.90$. Similar quantum interference was observed even when the tunable filter of 0.9-nm bandwidth was removed, although the visibility was degraded to $V \sim 0.6$. These results

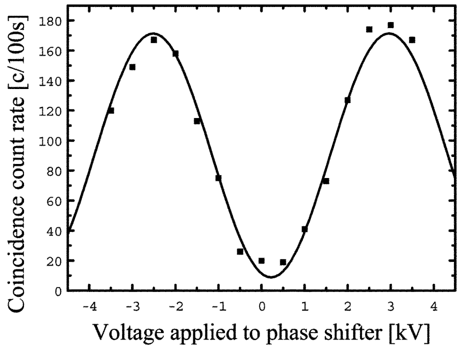

Fig. 3. Experimentally observed photon intensity interference.

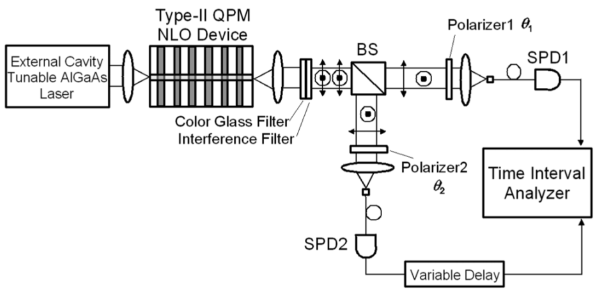

Fig. 4. Setup for twin-photon polarization measurement.

indicate that the polarization entangled states of (4) were generated.

IV. Entangled Photon Polarization Measurement

It can readily be shown that the polarization entangled state (3) is invariant with respect to rotation of polarization basis. Let XY be basis axes rotated by an angle θ with respect to the xy (HV) basis axes. Then the invariance can be described as

$$|\psi\rangle = \sqrt{1/2}\{|x;y\rangle - |y;x\rangle\} = \sqrt{1/2}\{|X,Y\rangle - |Y,X\rangle\} \quad (6)$$

and it reflects the nondeterministic and nonlocal nature of the polarizations of entangled photons. Such a nature can be examined by polarization-selective photon coincident counting experiment. Let θ_1 and θ_2 be the angles of the basis rotation for the output ports 1 and 2, respectively. Then a simple theoretical calculation for the state (6) shows that the rate of coincidence counting for X polarized photons in each port is proportional to

$$P_{XX} = \left\langle \psi \left| a_{1X}^{\dagger} a_{2X}^{\dagger} a_{2X} a_{1X} \right| \psi \right\rangle = (1/2)\sin^2(\theta_1 - \theta_2). \quad (7)$$

Fig. 4 shows the setup for the polarization-selective photon coincident counting experiment. Polarizers were inserted in front of the two SPDs, and the CCR was measured by using a TIA. Fig. 5 shows the measured dependence of the CCR on the orientation θ_1 of polarizer 1 for a few fixed angles θ_2 of polarizer 2. The result shows the periodic modulations consistent with the theoretical prediction given by (7). The deviation of the result from (7) would be due to the polarization-dependent waveguide losses, and difference in the detector efficiency and coupling efficiency between the output port 1 and 2. The potential way of performance improvement would be to reduce the waveguide losses by waveguide burying and/or reduction of

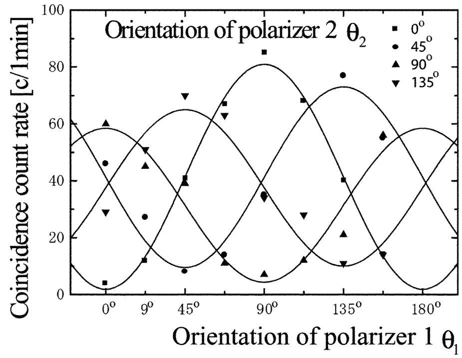

Fig. 5. Coincidence count rate dependent on polarizer orientation.

surface roughness. The result, however, clearly demonstrates the nondeterministic and nonlocal nature of the polarizations of entangled photons, since the result cannot be explained by the classic model.

V. Conclusion

We demonstrated the generation of polarization entangled twin-photon beams in a simple optical system using a Type-II QPM waveguide NLO device for the first time.

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