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Cite as: APL Photonics 5, 036104 (2020); <https://doi.org/10.1063/1.5142437>

Submitted: 13 December 2019 . Accepted: 01 March 2020 . Published Online: 30 March 2020

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Takahiro Kashiwazaki,^{1,a)} Naoto Takanashi,² Taichi Yamashima,² Takushi Kazama,¹ Koji Enbutsu,¹ Ryoichi Kasahara,¹ Takeshi Umeki,¹ and Akira Furusawa^{2,b)}

AFFILIATIONS

¹NTT Device Technology Labs, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan

²Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

^{a)} Author to whom corresponding should be addressed: takahiro.kashiwazaki.dy@hco.ntt.co.jp

^{b)} Electronic mail: akiraf@ap.t.u-tokyo.ac.jp

ABSTRACT

Terahertz (THz)-bandwidth continuous-wave (CW) squeezed light is essential for integrating quantum processors with time-domain multiplexing (TDM) by using optical delay line interferometers. Here, we utilize a single-pass optical parametric amplifier (OPA) based on a single-spatial-mode periodically poled ZnO:LiNbO₃ waveguide, which is directly bonded onto a LiTaO₃ substrate. The single-pass OPA allows THz bandwidth, and the absence of higher-order spatial modes in the single-spatial-mode structure helps avoid degradation of squeezing. In addition, the directly bonded ZnO-doped waveguide has durability for high-power pump and shows small photorefractive damage. Using this waveguide, we observe CW 6.3-dB squeezing at 20-MHz sideband by balanced homodyne detection. This is the first realization of CW squeezing with a single-pass OPA at a level exceeding 4.5 dB, which is required for the generation of a two-dimensional cluster state. Furthermore, the squeezed light shows 2.5-THz spectral bandwidth. The squeezed light will lead to the development of a high-speed on-chip quantum processor using TDM with a centimeter-order optical delay line.

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I. INTRODUCTION

Quantum information processing (QIP) with quadrature amplitudes of light is promising for realizing deterministic, universal, and fault-tolerant operation.^{1,2} In particular, continuous-wave (CW) light enables efficient implementation of large-scale QIP with time-domain multiplexing (TDM) by using delay line interferometers.³ This is because CW light provides full utilization of processing time, unlike pulsed light, which wastes most of the time due to its low duty ratio. Applying TDM for QIP enables us, in principle, to generate unlimited scales of quantum entanglement in finite space.^{1,4} Recently, large-scale quantum entanglement of over one-million states⁵ and two-dimensional (2D) cluster states⁶ have been successfully demonstrated by using TDM.

In the TDM scheme, generation of broadband CW squeezed light is essential for speeding up and downsizing quantum

processors. A wide bandwidth is desired for high-speed quantum processing because the maximum clock rate of a quantum processor is limited by the bandwidth of the quantum resource, namely, squeezed light. At the same time, the wide bandwidth contributes to downsizing the system. Terahertz (THz)-order broadband squeezed light allows us to define micrometer-order wave-packet modes, which require a delay line with only 3-cm optical length for a cluster state with one-hundred entangled modes for quantum computing. The downsizing enables us to integrate the processors into a silica-based optical chip.^{7,8}

For a quantum processor, not only broadband light but also high-level squeezing is required to obtain the “quantum” effect, such as at least 3 dB for entanglement swapping^{8,9} and 4.5 dB for the generation of 2D cluster states.⁶ Since the first observation of squeezed light in 1985,¹⁰ various approaches have been used to achieve high-level squeezing.¹¹ However, over 4.5-dB squeezing, which is

required for the generation of 2D cluster states, has not yet been achieved for CW light with a THz bandwidth.

To obtain high-level CW squeezed light, an optical parametric oscillator (OPO) is usually used with a second-ordered nonlinear optical crystal inserted into an optical cavity, which enhances the optical parametric process. The CW squeezing levels of 7.2 dB, 9.0 dB, and 15.3 dB were achieved in 2006,¹² 2007,¹³ and 2016,¹⁴ respectively. Although these experimental results have demonstrated the high squeezing level required for practical application, the squeezing bandwidth is limited by the cavity-based configuration itself. Even with a monolithically integrated OPO, the bandwidth of the squeezing light is up to 2.5 GHz.¹⁵

The use of a single-pass traveling-wave optical parametric amplifier (OPA) is an attractive way to obtain broadband squeezed light. Squeezing with THz bandwidth has been demonstrated, thanks to the wide bandwidth of OPAs, which is, in principle, limited only by the transparency or phase-matching conditions of the nonlinear medium itself.¹⁶ One way to achieve a high squeezing level from a single-pass OPA is to pump it with pulsed light, which instantaneously provides large electric-field amplitude.^{17,18} The drawback of using pulsed light lies in the requirement of shaping a local oscillator (LO) spatiotemporally to match with the generated squeezed light.^{19,20} In particular, spatial mode matching is difficult because the phase front of the squeezed light from a single-pass OPA is distorted by gain-induced diffraction (GID) in a nonlinear crystal with high parametric gain.^{21,22} With spatiotemporally matched LO pulses, 5.8-dB squeezing was obtained from a type II KTiOPO₄ (KTP) crystal in 1994,²¹ which stood as the world record with a single-pass OPA system for over 20 years. In the CW scheme, OPAs require an alternative way to enhance nonlinearity without a cavity configuration and high-peak-power pumping scheme. In 1995, 0.7-dB squeezing was demonstrated using a waveguide device,²³ which provides high nonlinearity by finely confining light in a small core through its long interaction length.^{24,25} Waveguide devices have also yielded a reduction of the GID effect, thanks to good spatial mode overlapping.^{26,27} In addition, there is no temporal mode mismatching in the CW-pumping scheme. So far, 2.0-dB²⁸ and 2.2-dB²⁵ squeezing have been demonstrated by using CW-pumped OPAs based on highly efficient periodically poled LiNbO₃ (PPLN) and KTP waveguides, respectively.

To increase the squeezing level with a waveguide, we have to overcome drawbacks arising from the waveguide configuration and the CW-pumping scheme. In a waveguide, high-order spatial modes degrade the measurable squeezing level for the fundamental mode because the waveguide's output can be a mixture of a squeezed quadrature in the fundamental mode and anti-squeezed quadratures in higher-order modes. In the CW-pumping scheme, the issue is the resistance for high-power pumping. In nonlinear crystal waveguides, pump-induced optical scattering, known as the photorefractive effect,^{29,30} is inevitable because the average power required for CW-pumping OPA systems is over one hundred times higher than that for pulsed-pumping ones.

In this paper, we report the detection of 6.3-dB CW squeezed light at 20-MHz sidebands using a single-mode PPLN waveguide directly bonded onto a LiTaO₃ substrate. The bandwidth of the squeezed light is estimated to be 2.5 THz from the parametric fluorescence spectrum. The single-mode structure avoids

contamination of the squeezed quadrature by the anti-squeezed quadratures of higher-order spatial modes. The core material of lithium niobate was doped with ZnO. The directly bonded ZnO-doped PPLN waveguide has durability for high-power pump and shows small photorefractive damage with an over-100-mW CW pump at 20 °C. The squeezing level is high enough for the generation of 2D cluster states, which require squeezed light of over 4.5 dB as a resource. Furthermore, the result breaks the records of both single-pass CW 2.2-dB squeezing achieved with a periodically poled KTP waveguide in 2009²⁵ and single-pass pulsed 5.8-dB squeezing with a bulk KTP crystal in 1994.²¹

II. DEVICE DESIGN AND FABRICATION

To detect higher squeezing levels from a waveguide OPA, it is important to realize a highly efficient optical parametric process, low-loss detection, and high-power pump injection, as described in Ref. 23,

$$R_{\pm} = 1 - \eta + \eta \times \exp(\pm 2\sqrt{aP}), \quad (1)$$

where R_{-} is the squeezing level, R_{+} is the anti-squeezing level, η is the total effective detection efficiency for the generated squeezed light, a is the second-harmonic (SH) conversion efficiency of the waveguide OPA, and P is the pump power in the waveguide. Recently, higher values of nonlinear coefficient a have been obtained, thanks to improvements in waveguide fabrication technologies.³¹ On the other hand, P and η are remaining issues. The acceptable pump power of the waveguide is limited by pump-induced phenomena such as photorefractive damage.^{29,30} Therefore, we need to improve the durability of the core material for high-power pump light so that the pump power can be increased with a low photorefractive effect. Regarding optical loss, η can be divided into several factors as expressed by

$$\eta = (1 - L_{WG})(1 - L_{HD}). \quad (2)$$

Here, L_{WG} and L_{HD} are the effective transmission loss of the waveguide for squeezed light and the measurement loss of homodyne detection, respectively.

L_{WG} includes the intrinsic loss of optical materials, extrinsic loss derived from structural imperfections in the waveguide, and pump-induced loss of the nonlinear optical crystals. To reduce the pump-induced loss, a highly durable nonlinear crystal for a high-power pump should be used. In addition, to maintain durability for a high-power pump, it is important to avoid deteriorating the crystal quality during waveguide fabrication. As described before, when these requirements are met, we can not only suppress the loss but use a high-power pump as well, which is desired for the generation of high-level squeezed light.

The homodyne detection loss, L_{HD} , is derived from the spatiotemporal mode mismatch with an LO, photo-electric conversion loss of photodiodes, and electrical circuit noise equivalent to optical loss. The circuit noise can be made negligibly small by using sufficient LO power. A quantum efficiency of up to 99% has been achieved for detectors, thanks to the recent improvements in fiber optic components for telecommunications.³² However, mode-mismatch is still a problem in single-pass OPA squeezing. In CW squeezing, the problem is spatial mode-mismatch rather than temporal mode-mismatch. The difficulty of spatial mode-match has

often been addressed by considering GID,²¹ which is caused by a difference in the spatial-modal-shape between the pump and the squeezed light in a nonlinear bulk crystal with a single-pass amplification scheme. The phase front of the squeezed light is distorted by GID in a high-parametric-gain regime. It has been reported that using a waveguide can suppress GID,^{26,27} however, a similar problem is thought to occur in a multi-mode waveguide. The generated squeezed light in a multi-mode waveguide contains various spatial modes, and the phase and amplitude of each mode have a complex relationship. Therefore, it is difficult to shape the LO to have completely the same optical phase-amplitude distribution as the squeezed light, even though mode-shaping techniques are used for LOs. For this reason, the measured squeezing quadrature is usually contaminated by anti-squeezing quadratures from higher-order spatial modes. Here, one of the solutions is to use a single-mode waveguide, which can completely eliminate the contamination problem of a spatially multi-mode OPA.

For the single-mode propagation of squeezed light, we calculated a modal dispersion curve of a waveguide by using the finite-difference method (Optiwave System Inc., OptiBPM 12). Here, we assumed ZnO-doped PPLN as a core material for its high second-order nonlinearity and broadband transparency. ZnO is used as a dopant to suppress the photorefractive effect of lithium niobate.³³ In the calculation, we assumed a core thickness of $5.0\ \mu\text{m}$, as shown in Fig. 1(a). The shape of the cross section of the waveguide is trapezoidal, which is inevitable due to the redeposition of lithium niobate

in the dry etching process.³⁴ Our waveguide has a side wall angle of 73.5° on both sides. Figure 1(b) shows effective refractive indices of three modes for vertically polarized 1550-nm light as a function of waveguide-top width. The insets show modal amplitude distributions for fundamental, second-order, and third-order modes with the waveguide-top widths of $4.0\ \mu\text{m}$, $6.5\ \mu\text{m}$, and $11.0\ \mu\text{m}$, respectively. The higher-ordered modes are allowed to exist in the region with over $6.5\text{-}\mu\text{m}$ top width. Generally, a large size core is tolerant against fabrication errors, such as the roughness of the waveguide core's side walls. Thus, we decided to make the waveguide-top width about $6.0\ \mu\text{m}$, which is the maximum width for the single-mode condition at the wavelength of $1550\ \text{nm}$.

We fabricated a ZnO-doped PPLN waveguide by direct bonding and dry etching.³⁵ The waveguide length was $45\ \text{mm}$. The quasi-phase-matching pattern was fabricated by using the electrical poling process with the poling period of about $18\ \mu\text{m}$. Both the input and output end-faces of the waveguide were mechanically polished and covered with an anti-reflection (AR) coating for both 1550-nm and 775-nm light. Figure 1(c) shows cross-sectional and perspective views of the fabricated PPLN waveguide observed by scanning electron-beam microscopy. The waveguide was directly bonded onto a LiTaO_3 wafer, whose thermal expansion coefficient is close to that of lithium niobate. The bonded waveguides showed high durability for high-power second-harmonic (SH) pump light and high-efficiency optical parametric conversion,^{31,36} compared to a waveguide fabricated with the titanium diffusion method.³⁷ The

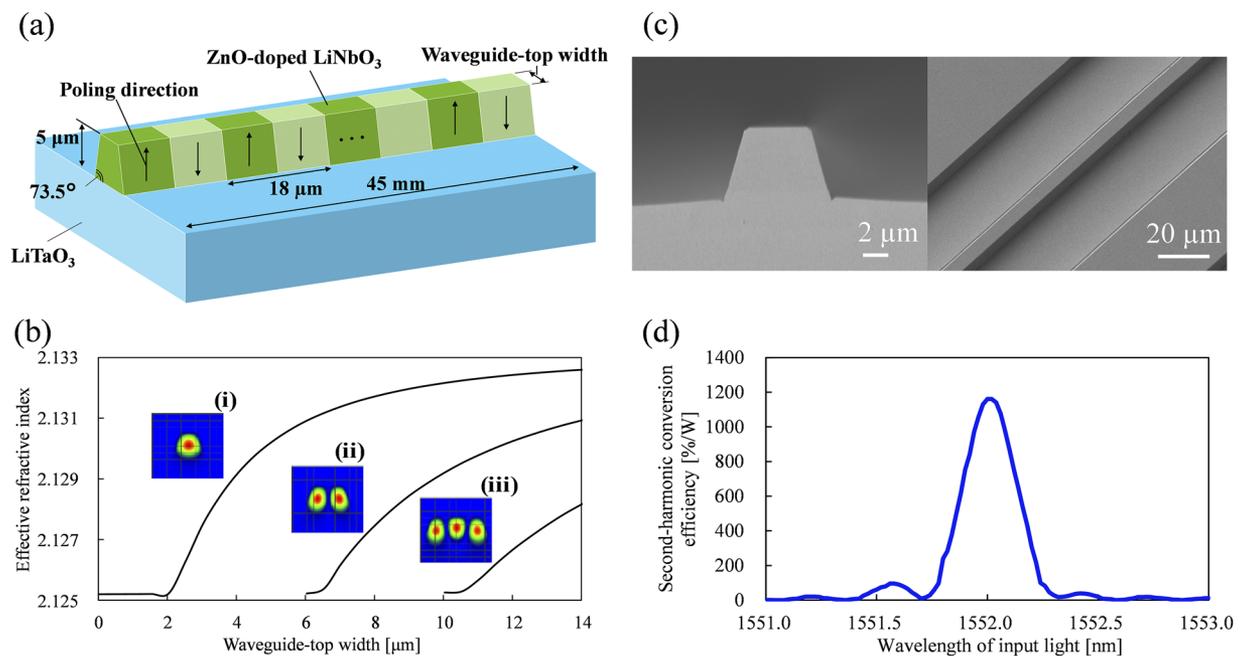


FIG. 1. (a) Schematic view of the fabricated PPLN waveguide. (b) Modal dispersion curve for the PPLN waveguide calculated by using the finite differential method. Effective refractive indices for three modes as a function of waveguide-top width are shown. (i) First-order mode, namely, the fundamental mode, with a waveguide-top width of $4.0\ \mu\text{m}$. (ii) Second-order mode with a waveguide-top width of $6.5\ \mu\text{m}$. (iii) Third-order mode with a waveguide-top width of $11.0\ \mu\text{m}$. Calculated shape for each mode is also shown. The waveguide structure was assumed to be fabricated with the dry etching method. The thickness of the core was $5.0\ \mu\text{m}$, and the wall angles of the waveguide were 73.5° . (c) Cross-sectional and perspective views of the PPLN waveguide taken with scanning electron-beam microscopy. The PPLN waveguide is directly bonded onto a lithium tantalate substrate. (d) Second-harmonic conversion efficiency of the fabricated PPLN waveguide. A power of input light was $3\ \text{mW}$.

ion diffusion process causes a defect in the core crystal of the waveguide and deteriorates the durability for high-power pump light.³⁸ Figure 1(d) shows the phase-matching curve of the fabricated PPLN waveguide at 45 °C. The SH-conversion efficiency was estimated by the powers of output SH light and input 3-mW fundamental light. At the center wavelength of 1552 nm, our waveguide shows 1160% W⁻¹ of SH-conversion efficiency.

III. EXPERIMENTAL RESULTS

A. Squeezing-level measurement

Figure 2 shows the experimental setup for the detection of a squeezed vacuum from a fabricated PPLN waveguide (PPLN-WG1). CW light from a fiber laser at a wavelength of 1550.0 nm (NKT Photonics, Koheras BOOSTIK) was distributed into two optical fibers by an optical fiber beamsplitter (Thorlabs, PN1550R2A1). Both beams passed through variable optical attenuators (VOA1 and VOA2) (Thorlabs, VOA50PM-APC). One beam was injected into a frequency doubler based on a PPLN waveguide (NTT Electronics, WH-0776-000-F-B-C). A frequency-doubled beam was used as a pump beam for the PPLN-WG1 and generated squeezed light according to the optical parametric process. The temperature of PPLN-WG1 was about 20 °C, which was controlled by using a Peltier device to keep phase-matching conditions for 1550 nm. The squeezed vacuum was separated from the SH pump beam by a dichroic mirror (DM). The other output from the fiber beamsplitter was used as an LO. For homodyne detection, the squeezed vacuum gets interfered with the LO at the 50/50 beamsplitter (BS). A different PPLN waveguide (PPLN-WG2), which has the same structure as PPLN-WG1, was used as a beam shaper for the LO to get high spatial mode matching in the homodyne detection. Here, the visibility was about 0.98 in the experimental setup. We emphasize that the single-mode structures of PPLN-WG1 and PPLN-WG2 largely contributed to this high visibility. The phase-matched wavelength of PPLN-WG2 was intentionally detuned by controlling the waveguide

temperature to suppress second-order nonlinear processes, such as second-harmonic generation. The phase of the LO beam was scanned by using a phase modulator (Thorlabs, LN65-10-P-F-F-BNL) driven by a 500-mHz triangle wave signal. The homodyne detector consisted of specially ordered InGaAs photodiodes (Laser Components, IGHQEX0100-1550-10-1.0-SPAR-TH-40) and an AC-coupled transimpedance amplifier, which was also used in Ref. 32. The quantum efficiency of the photodiode is about 99% at 1550 nm. The output electric signal was measured by using an electrical spectrum analyzer (ESA) (Agilent, E4401B).

Figure 3(a) shows powers of squeezed vacuum noise and squeezed noise detected by a zero span measurement with the spectrum analyzer at the frequency of 20 MHz. The pump power injected into the waveguide was 304 mW, which was estimated by the power detected at PD3. The resolution bandwidth and video bandwidth were 5 MHz and 3 kHz, respectively. Detected noise was amplified and de-amplified by scanning the LO phase. Since the scan signal for the modulator was a triangle wave, the detected noise shows symmetrical shape centered at the sweep time of about 0.25 s. The measured squeezed and anti-squeezed noise levels are -6.3 ± 0.1 dB and 14.7 ± 0.1 dB, respectively. The shot noise level was measured by blocking the optical path soon after the PPLN-WG1. The power of the output LO beam from PPLN-WG2 was 8.9 mW. The measurement error was defined as the standard variation of shot noise of 0.1 dB. The circuit noise level of homodyne measurement was about -50 dBm, which is negligibly small compared to the shot noise level of about -30 dBm.

Figure 3(b) shows the squeezed and anti-squeezed noise levels as functions of pump power in PPLN-WG1. The pump power was controlled by VOA1. The squeezing levels and anti-squeezing levels were measured at the frequency of 20 MHz. The anti-squeezed noise levels increased with an increase in pump power. On the other hand, the squeezed noise levels saturated at about -6 dB due to the effective loss for squeezed light. This asymmetrical shape was caused by the contamination of the vacuum noise derived from the optical loss for squeezed light. In this experiment, the LO phase

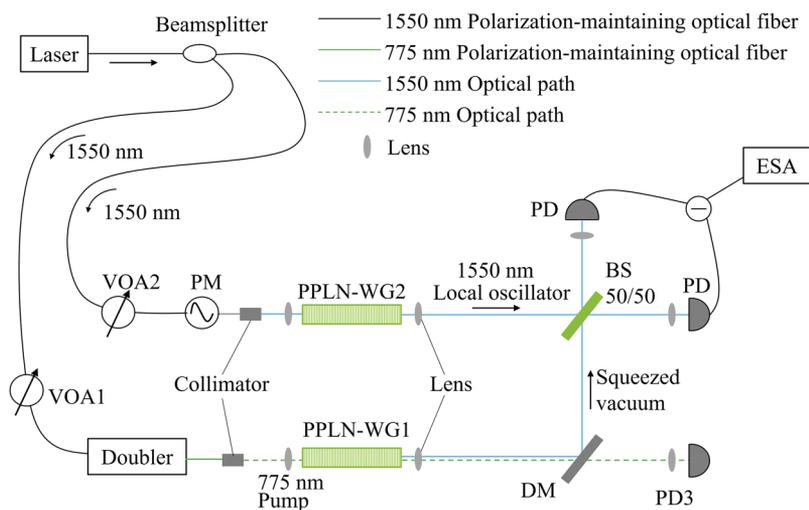


FIG. 2. Schematic diagram of the experimental setup for the detection of the squeezed light from a PPLN waveguide. BS: 50/50 beamsplitter. DM: dichroic mirror, which reflects the squeezed light and through pump light. PD: photodetector. VOA: variable optical attenuator. PM: optical phase modulator for phase scanning of homodyne detection. PPLN-WG1: PPLN waveguide for the generation of squeezed vacuum. PPLN-WG2: PPLN waveguide for mode shaping. ESA: electrical spectrum analyzer.

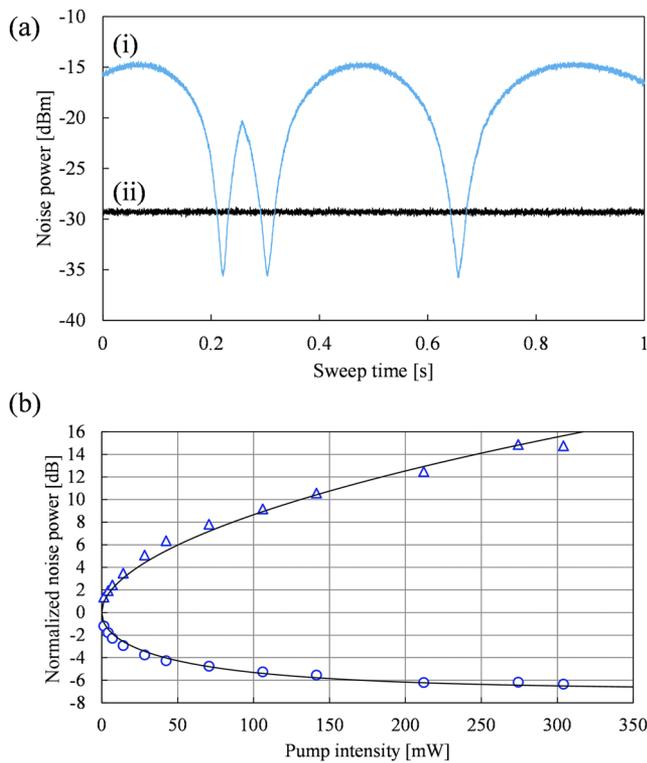


FIG. 3. (a) Raw data of noise power detected by homodyne detection as a function of sweep time with the phase scanning of the LO beam. (i) Noise of squeezed vacuum. (ii) Shot noise. The scan signal for the modulator is a 500-mHz triangle wave. The measurement frequency is 20 MHz. The resolution bandwidth is 5 MHz. The video bandwidth is 3 kHz. The intensity of the pump beam is 304 mW, measured by using PD3. The circuit noise level is lower than the shot noise level by more than 20 dB. (b) Squeezing and anti-squeezing levels as functions of pump intensities detected by using PD3. The levels are normalized by the intensity of shot noise. The measured noise powers were obtained at a fixed analysis frequency of 20 MHz. The resolution bandwidth is 5 MHz. The solid line is a fitting curve. The pump power in the PPLN-WG1 was estimated from the detected power at PD3.

scanning was much slower than the averaging time of the spectrum analyzer, and we could ignore waveform blunting due to the measurement setting. The solid fitting curves are drawn according to Eq. (1), and η and a are fitted to $0.79\% \text{ W}^{-1}$ and $1210\% \text{ W}^{-1}$, respectively. Considering the photodiode’s quantum efficiency of 0.99, the optical transmittance through the beamsplitter and the mirrors of 0.97, and the visibility of 0.98, the total transmittance for the output squeezed vacuum is 0.94, which is equivalent to an L_{HD} of 0.06. Therefore, the estimated effective loss in the PPLN waveguide, L_{WG} , is 0.16.

The anti-squeezed noise level exponentially increases as the SH-pump power increases, even when it reaches over 100 mW. Furthermore, the estimated SH-conversion efficiency of $1210\% \text{ W}^{-1}$ is consistent with the obtained value of $1160\% \text{ W}^{-1}$, which was estimated from the measurement of SH-conversion efficiency with a 3-mW 1.5- μm -wavelength pump light shown in Fig. 1(d). These results indicate that our waveguide provides a highly efficient optical parametric process without degradation due to pump-induced loss,

such as that due to photorefractive damage. In addition, our PPLN waveguide works at 20°C , indicating that the directly bonded ZnO-doped PPLN waveguide has high durability for high-power pumping compared to other nonlinear waveguides that must be operated at a high temperature for suppressing photorefractive damage.^{33,39} A higher squeezing value could be obtained by improving the fabrication process to reduce L_{WG} , especially the optical propagation loss due to structural imperfections. Realization of higher SH-conversion efficiency would also be important, for example, by using a smaller core waveguide.⁴⁰

B. Bandwidth measurement of squeezed light

To estimate the bandwidth of the squeezed light, we measured squeezing levels at various frequencies with the same experimental setup as shown in Fig. 2. Figure 4 shows the observed noise power at each frequency from 10 MHz to 1 GHz. The resolution bandwidth was 5 MHz. The shot noise and the circuit noise are also shown. The circuit noise was detected by blocking both ports of the homodyne detector. At up to 250 MHz, the squeezing levels stayed over 4.5 dB, which is the value required for generating a 2D cluster state. Above 300 MHz, the squeezing levels decreased with a decrease in electrical circuit noise. This means that the measured squeezing level in the high-frequency range was limited by the measurement capability of the homodyne system, such as the bandwidth of the photodiodes.

In order to estimate an actual squeezing bandwidth, we measured the optical spectrum of the squeezed light from a fabricated PPLN waveguide (PPLN-WG1). Figure 5(a) shows the experimental setup. The optical components in the setup were the same as those used in the measurement for squeezing levels (Fig. 2). The squeezed light from PPLN-WG1 was separated from a SH beam by a dichroic mirror (DM) and injected into an optical spectrum analyzer (OSA) (Anritsu, MS9710C). Figure 5(b) shows the spectra at various pump powers. The optical resolution and video bandwidth were 50 pm and 100 Hz, respectively. The squeezed light, consisting of pairs of signal and idler photons, has an almost symmetrical shape with a center

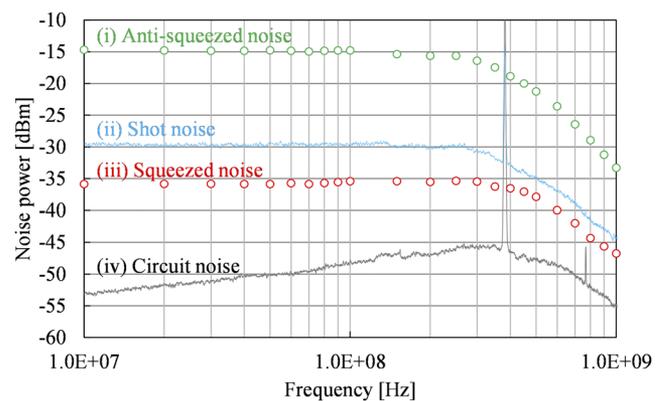


FIG. 4. Measured noise powers detected at various frequencies. (i) Anti-squeezed noise. (ii) Shot noise. (iii) Squeezed noise. (iv) Circuit noise. The resolution bandwidth is 5 MHz. The circuit noise was detected by blocking both ports of the homodyne detector.

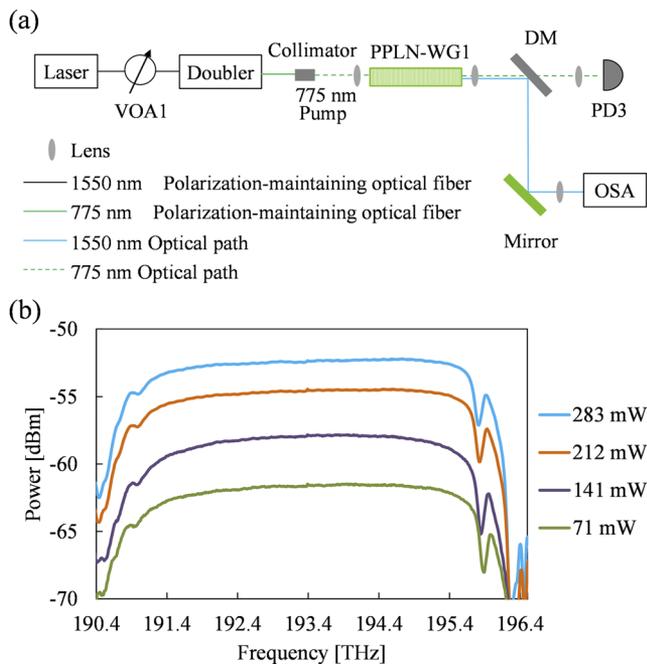


FIG. 5. (a) Schematic diagram of the experimental setup for the detection of the squeezed light from a PPLN waveguide by using an optical spectrum analyzer. DM: dichroic mirror, which reflects the squeezed light and through pump light. PD3: photodetector for pump light. VOA: variable optical attenuator. PPLN-WG1: PPLN waveguide for the generation of squeezed light. OSA: Optical spectrum analyzer. (b) Spectrum of squeezed light with various powers of pump light, detected by using an optical spectrum analyzer. The pump power was estimated from the power detected at PD3. Optical resolution and video bandwidth are 50 pm and 100 Hz, respectively.

frequency of 193.4 THz, corresponding to a center wavelength of 1550 nm. The generated squeezed light has 2.5-THz bandwidth as its half width at half maximum, which directly represents the squeezing bandwidth.⁴¹ To maintain and utilize this broad bandwidth for actual applications, it is important to prepare optical components with low dispersion for squeezed light or to use inverse dispersion media for dispersion compensation. Furthermore, using integrated high-speed electro-optic devices⁴² and using a broadband detection technique with an optical parametric amplifier⁴³ will lead to realize high-speed on-chip quantum processors.

IV. CONCLUSION

In summary, we detected CW 6.3-dB-squeezed light at 20 MHz sidebands by using a single-mode PPLN waveguide directly bonded onto a LiTaO₃ substrate. Squeezing at over 4.5 dB was measured up to a frequency of 250 MHz by balanced homodyne measurement. The actual bandwidth of the squeezed light is estimated to be 2.5 THz by measurement of its optical spectrum. The single-mode structure avoids contamination of the squeezed quadrature by the anti-squeezed quadrature of higher-order spatial modes. The directly bonded ZnO-doped PPLN has durability for high-power pump and shows small photorefractive damage with a CW pump of over 100 mW at 20 °C. The squeezed light with a bandwidth

exceeding 1 THz will enable us to define micrometer-order wavepacket modes, which requires only a delay line with 3-cm optical length in differential interferometers for hundreds of entangled modes in QIP with TDM. This means that the squeezed light will open the possibility of large-scale QIP with a small optical system, such as with an integrated optical chip. We believe that our results will lead to the development of a high-speed optical quantum processor with a large-scale cluster state.

ACKNOWLEDGMENTS

This work was supported by the Core Research for Evolutional Science and Technology (CREST) (Grant No. JPMJCR15N5) of the Japan Science and Technology Agency (JST); KAKENHI (Grant No. 18H05297) of the Japan Society for the Promotion of Science (JSPS); APLS of the Ministry of Education, Culture, Sports, Science and Technology (MEXT); and the University of Tokyo Foundation. The author acknowledges Asuka Inoue and Yoshiki Nishida for their useful comments on the manuscript.

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