Observation of Robust Polarization Squeezing via the Kerr Nonlinearity in an Optical Fiber

Nikolay Kalinin,* Thomas Dirmeier, Arseny A. Sorokin, Elena A. Anashkina, Luis L. Sánchez-Soto, Joel F. Corney, Gerd Leuchs,* and Alexey V. Andrianov

Squeezed light is one of the resources of photonic quantum technology. Among the various nonlinear interactions capable of generating squeezing, the optical Kerr effect is particularly easy-to-use. A popular venue is to generate polarization squeezing, which is a special self-referencing variant of two-mode squeezing. To date, polarization squeezing generation setups have been very sensitive to fluctuations of external factors and have required careful tuning. In this work, a development of a new all-fiber setup for polarization squeezing generation is reported. The setup consists of passive elements only and is simple, robust, and stable. More than 5 dB of directly measured squeezing is obtained over long periods of time without any need for adjustments. Thus, the new scheme provides a robust and easy-to-set-up way of obtaining squeezed light applicable to different applications. The impact of pulse duration and pulse power on the degree of squeezing is investigated.

1. Introduction

Squeezed light refers to a unique set of quantum states of the electromagnetic field,[1,2] playing an important role in photonic quantum technologies.[3,4] The term refers to a phase-space description and is used whenever the volume of the quantum uncertainty in phase space is squeezed, so that a variable such as a particular field quadrature has a variance smaller than the one of a coherent state. After the first observation of squeezing,[5] many groups studied the various schemes for the generation, the detection, and applications of squeezed states of light as reviewed 30 years later.[6] Since then, the field progressed further for example, with the demonstration of interferometric sensitivity enhancement in kilometer-sized gravitational wave detectors[7] and with the proposal[8] and subsequent experimental demonstrations[9,10] of Gaussian Boson sampling — two important hallmark milestones in different pillars of quantum technology. Quantum sensing with squeezed light continues to strive.[11] The theoretical concept of squeezed states is, however, much older.[12] The following two types of squeezed states of a single mode of light are the most common ones: 1) squeezed vacuum states and 2) squeezed coherent states. Note that squeezed vacuum states can be “bright” containing many photons.[13] A state squeezed along a line is a Gaussian state, like a coherent state, and is described by a positive-valued Wigner function. In some applications, there still has to be a non-Gaussian element. When combining squeezed states with linear optical networks, non-Gaussianity can be achieved by using nonlinear, that is, non-Gaussian detectors, such as single-photon or photon-number-resolving detectors.[14] This applies to both types of squeezed states, but depending on how many photons such a detector can handle, type (1) squeezed states could be preferable. Note, that...
there are also nonlinear squeezed states, for example, squeezed along a bent line, which are non-Gaussian by definition\cite{15} and could become a valuable resource. In principle, any nonlinear optical light matter interaction\cite{16} will change the photon statistics, potentially leading to squeezing, but sizeable squeezing can only be observed if at the same time losses are low enough.\cite{16} Therefore, a preferred nonlinear interaction is a nonresonant $\chi^{(2)}$ interaction in a low-loss crystal, which straightforwardly can generate type (1)\cite{17} and also type (2)\cite{18} squeezed light. However, this method requires a special material class without inversion symmetry as the optically nonlinear material and a phase-matching condition has to be fulfilled. Nevertheless, this is probably the generation scheme used most often so far in applications.\cite{19} A conceptually more simple scheme generating primarily type (2) squeezed light is based on the optical Kerr effect, that is, the nonresonant $\chi^{(3)}$ interaction. Note, that Kerr squeezing can be generated also by a cascaded $\chi^{(2)}$ interaction\cite{20} which facilitates the observation of seeing the effect for continuous-wave light.\cite{21} Here, we report on a novel scheme for generating Kerr polarization squeezing in a robust way.

2. State of Kerr Effect Squeezing of Light

All materials show the Kerr effect, including standard telecommunication fibers, which have the additional benefit of having very small optical losses. The catch is that the Kerr effect changes the photon statistics such as to generate type (2) squeezed light introducing amplitude-phase correlations, resulting in a squeezing ellipse in phase space oriented in a skewed direction, neither in the direction of the amplitude nor in that of the phase quadrature. As a result, the detection of Kerr squeezing has been a challenge. Kerr squeezing can be viewed as four-wave mixing: two photons are annihilated at the pump frequency, that is, the carrier frequency, and one photon each are generated symmetrically in an upper and lower sideband, not too different from the $\chi^{(2)}$ scheme, only that there the carrier in between is missing.\cite{19,22,23} In the regime of anomalous dispersion in a sodium dioxide glass wave guide, phases are matched in a wide spectral range, leading to a correspondingly large noise bandwidth of more than a THz.\cite{24} As a result, the sideband frequency can not only be small for example, in the radio-frequency range but also large, closer to optical frequencies. In any case, when performing direct detection of the resulting field, no effect of this Kerr interaction is to be seen because the number of photons is unchanged. Alternatively, in the single-mode phase-space picture, the different amplitudes within the uncertainty of the initial coherent state experience amplitude dependent phase shifts, resulting in the skewed ellipse so that the overall amplitude uncertainty is unchanged.

The group first studying this generation scheme in an optical fiber with a continuous wave light beam\cite{25} used dispersive back reflection from an optical cavity\cite{26,27} to adjust the squeezed ellipse orientation, such that squeezing was detectable in direct detection.\cite{28,29} But they struggled with phase noise in the fiber due to scattering on the thermally excited acoustic modes of the fiber, for which they coined the expression “guided acoustic wave Brillouin scattering” (GAWBS). The observed squeezing was minute. Next, the idea came up to use optical soliton pulses instead.\cite{30,31} which do not disperse and keep their peak power. So, the effective Kerr nonlinearity was considerably higher, allowing one to use shorter fibers, which reduces GAWBS. In addition, this new approach used a symmetric fiber Sagnac interferometer, where one output contains approximately a squeezed vacuum and the other one a bright state that can be used as a local oscillator to probe the squeezing.\cite{30,32,33} Both outputs experience approximately similar GAWBS noise, so that it largely cancels. As it turned out, this scheme works well if the beam splitting ratio is exactly 50%/50% over the whole spectrum and the performance quickly deteriorates even when the deviation is only small.\cite{31} But yet another route to observable squeezing was found: photons in different frequency bands typically show correlations. It is only when you sum over them that there is no observable effect of the Kerr interaction. Friberg\cite{35} recognized that if one perturbs this balance, it is possible to observe a sub shot-noise signal in direct detection, or quantum correlated signals when detecting different frequency bands separately. Of course, again optical soliton pulses were used. Such spectral manipulation is possible with a grating spectrometer, if the frequency spacing is sufficiently large,\cite{36} or with a highly dispersive interferometer when the frequency spacing is in the radio frequency regime.\cite{37,38} This scheme is closely related to parametric amplification with four-wave mixing\cite{39} and to quantum frequency combs.\cite{40–42} The fourth route to observable Kerr squeezing in a fiber was to follow the proposal by Kitagawa and Yamamoto\cite{43} and use an asymmetric Sagnac loop to displace the squeezing ellipse in phase space such that the short axis lines up with the amplitude quadrature.\cite{44} The scheme was recently used for precision transmission measurements.\cite{45} All the Sagnac interferometer setups have the common problem that at most locations along the fiber, the counter propagating fields probe the GAWBS at different times, so some degradation because of GAWBS is persisting. Therefore, new schemes were invented with two co-propagating pulses. A first type was still following Kitagawa and Yamamoto, but unfolding the Sagnac interferometer leading to single mode squeezed light.\cite{51,52} The second type\cite{53,54} uses two equally intense pulses emerging from two separate and independent Kerr interactions in a linear polarization preserving fiber, one soliton pulse propagating along the fast and the other one along the slow axis such that the two coincide at the fiber output. But this time one is not trying to interfere the two pulses to produce single mode squeezed light. Rather, the measured noise reduction is now a property of both modes and one describes it as polarization squeezing which is a special variety of the more general concept of two-mode squeezing.\cite{55,56} The two light fields are analyzed using the SU(2) description\cite{57} and visualizing this system of two modes on the Poincaré sphere.\cite{58} There is an interesting dynamics of the Wigner function on the sphere as a result of the Kerr interaction.\cite{59,60} Note, that measuring the Stokes parameters spanning the Poincaré sphere again involves interference and it can be done with direct detection without any additional local oscillator. In this sense, one might say that one beam serves as the local oscillator of the other one and vice versa and that this system of two beams is self-referencing. GAWBS is reduced much further because of the co-propagation of the beams. This has been the fiber setup generating the highest squeezing so far.\cite{61}
3. All Fiber Kerr Squeezing

In this work we present a major modification of this copropagating scheme, providing greater stability due to an all-fiber passive design. In this novel setup, a polarization squeezed beam is produced when two equally bright pulses — simultaneously propagating in orthogonal polarization modes of a polarization-maintaining fiber — are recombined at the exit of the fiber. Each of these initially coherent pulses experiences Kerr squeezing while traveling through the fiber, changing its shape in phase space to a squeezed ellipse. When two such squeezed beams are combined in orthogonal modes, a polarization squeezed beam emerges, in which the variance of one of the Stokes parameters is lower than that in a coherent state with the same intensity. We define the quantum Stokes parameters as follows

\[
\hat{S}_0 = \hat{a}_H^\dagger \hat{a}_H + \hat{a}_V^\dagger \hat{a}_V, \quad \hat{S}_1 = \hat{a}_H^\dagger \hat{a}_V - \hat{a}_V^\dagger \hat{a}_H, \\
\hat{S}_2 = \hat{a}_H^\dagger \hat{a}_V + \hat{a}_V^\dagger \hat{a}_H, \quad \hat{S}_3 = i(\hat{a}_H^\dagger \hat{a}_V - \hat{a}_V^\dagger \hat{a}_H) \tag{1}
\]

where \(\hat{a}_H/V\) and \(\hat{a}_H^\dagger/V^\dagger\) are annihilation and creation operators in the horizontal (H) and vertical (V) polarization modes. The Stokes parameters can be directly measured using polarization splitting optics and two photodetectors. Actually, \(\hat{S}_0\) is proportional to the pulse energy, and the polarization is circular when that squeezing is detected when the short axis of the ellipse is parallel to the \(\hat{S}_1\) axis \((\theta = 0)\), and \(\Delta^2 \hat{S}_j < |\langle \hat{S}_j \rangle|\) \(\Delta^2 \hat{S}_2\). Polarization squeezing can then be sensibly defined in this case by

\[
\Delta^2 \hat{S}_1 < |\langle \hat{S}_1 \rangle| < \Delta^2 \hat{S}_2 \tag{2}
\]

where \(\Delta^2 \hat{S}_j\) denotes the variance \(\langle \hat{S}_j^2 \rangle - \langle \hat{S}_j \rangle^2\). Polarization squeezing can then be defined as

\[
\Delta^2 \hat{S}_1 \leq (\langle \hat{S}_j \rangle)^2 \tag{2}
\]

where \(\Delta^2 \hat{S}_j\) denotes the variance \(\langle \hat{S}_j^2 \rangle - \langle \hat{S}_j \rangle^2\). Polarization squeezing can then be sensibly defined in this case by

\[
\Delta^2 \hat{S}_1 < |\langle \hat{S}_1 \rangle| < \Delta^2 \hat{S}_2 \tag{3}
\]

Consider the 3D space with axes corresponding to the Stokes parameters \(S_1, S_2, S_3\), which is usually called the Poincaré space. This space appears foliated in terms of spheres, wherein each point corresponds to a certain polarization of the beam with a fixed power. When two Kerr squeezed beams are combined in orthogonal polarizations, the state of light is an ellipsoid in the Stokes parameters space, which is an ellipse in the projection on each Poincaré sphere (Figure 1). It is easy to position the center of this ellipse at the point corresponding to the circular polarization using standard optics, and after that continuously change its axes alignment angle \(\theta\) with a single half-wave plate. After that, we can measure the fluctuations in \(\hat{S}_1\) with a pair of balanced detectors by simultaneous measurement of optical power in the horizontal and vertical polarization modes and analyzing the difference signal. These fluctuations depend on the alignment angle \(\theta\), so we can write

\[
\Delta^2 \hat{S}_1 = \Delta^2 S_1 \cos^2 \theta + \Delta^2 S_2 \sin^2 \theta \tag{4}
\]

where \(\Delta^2 S_1\) denotes the lowest (squeezing) possible variance of \(\hat{S}_1\), and the \(\Delta^2 S_2\) denotes the highest (antisqueezing) variance. We see that squeezing is detected when the short axis of the ellipse is parallel to the \(\hat{S}_1\) axis \((\theta = 0)\), and \(\Delta^2 S_1 < |\langle \hat{S}_1 \rangle| < \Delta^2 S_2\). Note that it is impossible to know the angle \(\theta\) in experiment in advance, instead, the lowest and highest variances are found by rotating the half-wave plate. Thus, it is possible to analyze polarization squeezing without the use of an additional local oscillator, making polarization squeezing promising for applications.

Light propagates in two polarization modes of a polarization-maintaining fiber with different group velocities, thus a birefringence compensation is required to overlap the two pulses in time. In the original setup, a free-space interferometer was used to match the group delay, and a piezo-mounted mirror in one of the interferometer arms was used to control the relative phases of the two polarizations in a closed loop. In our new setup, we equalize the group delays by splitting the fiber into two equal lengths and rotating one of them by 90° around its axis. Thus, one of the two pulses travels first along the slow axis of the fiber, and then along the fast axis, while the other one travels first along the fast axis, and then the slow, resulting in equal group delay of both pulses. The two parts of the fiber are spliced with low losses, allowing the squeezing to aggregate over both parts of the fiber. Moreover, the relative phase drifts of the two pulses in our setup are very little and slow, because both pulses propagate through the same optical path and experience any thermal or mechanical changes equally. This advantage allows us to implement the setup without any active control loop; the polarization of the emerging beam is set to circular with the use of wave plates. Because of that, the setup is very stable.

4. Experimental Setup

The scheme of the experimental setup is shown in Figure 2. Two different setups with the same scheme were implemented (I and II). Femtosecond lasers (NKT Photonics Origami 15 LP, setup I, and Onefive Origami 15, setup II, these are Er-doped bulk crystal
lasers using a saturable absorber for mode locking) at 1560 nm were used as the source, with pulse duration of 200 fs (full width half maximum, FWHM, setup I), and adjustable duration of 235–370 fs (FWHM, setup II). The pulses were cosh-shaped temporally, allowing for easy soliton excitation in the fiber. The lasers were checked to be shot noise limited at the frequencies of interest. The repetition rate was 80 MHz with available pulse energy of up to 1.4 nJ. A gray filter (setup I) or a half-wave plate and a polarizer (setup II) were installed at the output of the laser to adjust the power, followed by a half-wave plate and a wave plate to adjust the linear polarization of the light launched to the fiber. Thus, both power and polarization of the light can be controlled, which is important to generate polarization squeezing. The polarization was adjusted so that it is 45° relative to the axes of the fiber, resulting in two pulses of equal power excited in two polarization modes in the fiber.

The polarization maintaining fiber used is 3M FS-PM-7811 of total length 5.2 m. The fiber was cut into two halves and spliced with a 90° rotation of the second half around its axis so that the slow axis of the first half is aligned with the fast axis of the second half and vice versa. The lengths of the halves differed by 3 cm to compensate for the unavoidable but small cross-phase-modulation-induced group delay difference, see the numerical modeling section for more details. The splicing losses were estimated to be 4%. After the fiber, the two pulses had an arbitrary relative phase, meaning that the polarization could be anywhere between the diagonal (45° to the fiber axis) and circular, so we used two quarter-wave plates to make the polarization of the beam circular. After that, a half-wave plate was used to rotate the uncertainty ellipse without changing the polarization of the light so that the minor axis of the ellipse is aligned with the H–V axis of the Poincaré sphere. The half-wave plate flips the clockwise circular polarization to counter-clockwise and vice versa, but it also changes the orientation of the squeezing ellipse depending on the orientation of the wave plate with respect to the fiber axes. Finally, the beam was split with a Wollaston prism into vertically and horizontally polarized components and detected with a pair of balanced detectors.

The signals from the detectors were low-pass-filtered to attenuate the high-amplitude signal at the 80 MHz pulse repetition rate. After that, the sum or the difference of the signals were fed to an electronic spectrum analyzer (ESA, Agilent E4411B (setup I), E4401B (setup II)). The noise power was detected at a radio frequency sideband of 15 MHz with the resolution bandwidth set to 100 kHz and a video bandwidth of 30 Hz. Thus, when the sum of the signals was detected at the ESA, effectively the variance of the power or the \( \hat{S}_0 \) Stokes component was measured. When the difference was detected, the variance of the \( \hat{S}_1 \) Stokes component was measured. All reported measurements were corrected for the electronic noise of −103.5 dBm measured in the absence of the light beam.

5. Results

The shot noise level was measured using the \( \hat{S}_0 \) variance measurement, it was also verified independently with a setup without the fiber. When the variance of \( \hat{S}_0 \) was measured, the result depended on the angle of the half-wave plate that changes the angle of the ellipse \( \theta \) on the Poincaré sphere (Figure 1). The lowest noise corresponded to the measurement of the squeezed axis of the fiber and defines the squeezing value, while the highest noise corresponded to antisqueezing. The dependence of the noise power on the alignment of the ellipse is shown in Figure 3a, perfectly matching the expected behavior. The maximum observed squeezing was > 5 dB.

When the beam is attenuated in front of the Wollaston prism, the expected dependence of the noise power on the transmission is given by

\[
\Delta^2_{\text{det}} = T \left[ \Delta^2 + (1 - T) \Delta^2_{\text{in}} \right]
\]

where \( \Delta^2_{\text{in}} \) is the detected noise, \( T \) is transmission, \( \Delta^2 \) is the noise of a nonattenuated beam, and \( \Delta^2_{\text{in}} \) is the shot noise at the same power. For a coherent beam, the dependence is linear, because \( \Delta^2 = \Delta^2_{\text{in}} \), and for a squeezed beam it is a parabola pointing downward. The noise levels of the squeezed beam measured in the experiment demonstrated parabolic dependence, confirming that genuine squeezing was seen (Figure 3b).

The squeezing generation was very stable without any adjustments, it deteriorated on a time scale of days due to environmental changes. The shot noise and squeezing noise for a period of 100 s are shown in Figure 4.

The losses of the detection setup were estimated to be 12% (4% from the fiber end, 6% from the optical elements, 2% from the quantum efficiency of the detectors). Additionally, in-fiber losses were estimated to be 8% (4% from the splice loss and 4% from the nonideal interference of the two polarization modes). Thus the inferred squeezing value assuming ideal detection setup is −6.5 dB, and assuming no losses in the fiber is −8.4 dB. We assume that the amount of squeezing in our setup was limited by the length of the fiber, and higher values can be achieved in future work using a longer piece of fiber.

The output pulse spectra for different powers are shown in Figure 5 together with the input spectrum. For the pulse energies close to fundamental solitons the spectrum almost does not change, except for a small shift toward longer wavelengths due

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**Figure 2.** The scheme of the experimental setup. The source emits 200–370 fs (FWHM) cosh-shaped pulses. The half-wave plate adjusts the polarization to be diagonal with respect to the polarization axes of the polarization-maintaining fiber. The second half of the fiber is rotated by 90° to compensate for the group delay difference. With two quarter-wave plates, the circular polarization is created after the fiber. The half-wave plate is used to align the minor axis of the uncertainty ellipse on the Poincaré sphere with the \( S_1 \) axis. Power in vertical and horizontal polarizations is separately detected, subtracted (or added up), and fed to an electronic spectrum analyzer. L, lenses; \( \lambda/2 \), half-wave plates; \( \lambda/4 \), quarter-wave plates; WP, a Wollaston prism.
Figure 3. a) Measured noise power depending on the alignment angle (squares), shot noise level (red dashed line), a fit of Equation (4) on experimental data (blue dashed line). Pulse duration (FWHM) 200 fs, pulse energy 160 pJ. b) Measured noise power depending on attenuation: shot noise (red circles, dashed is linear fit), squeezing (blue squares, dashed is parabolic fit (Equation (5)). Pulse parameters same as in (a), alignment angle $\theta = 0$.

Figure 4. Measured shot noise power (red circles) and squeezing of more than 5 dB (blue squares) over a period of 100 s. Pulse duration (FWHM) 200 fs, pulse energy 160 pJ, alignment angle $\theta = 0$.

Figure 5. Output spectra at pulse duration (FWHM) 235 fs, at different pulse energy with comparison to the initial spectrum of the pulse (dotted).

Figure 6. Measured squeezing for different pulse energies for the pulse duration (FWHM) of 200 fs (red plus), 235 fs (green stars), 310 fs (orange circles), and 370 fs (blue squares).

6. Numerical Modeling

To support our experimental results, we performed a series of numerical simulations. In order to calculate squeezing, we followed
a phase-space method using the Wigner representation described in detail in ref. [70]. The important effects this model includes are the second and third order dispersion, the instantaneous and the delayed (Raman) parts of the nonlinear $\chi^{(3)}$ response. For our fiber we measured and used in the modeling the following relevant parameters: second-order dispersion $\beta_2 = -10.5 \text{ fs}^2 \text{mm}^{-1}$, third-order dispersion $\beta_3 = 155 \text{ fs}^3 \text{mm}^{-1}$, effective nonlinearity $\gamma = 3.0 \times 10^{-3} \text{ W}^{-1} \text{m}^{-1}$. We also included linear losses in the fiber and in the detection scheme, which give 20% losses in total.

The previously developed model describes the quantum evolution of pulses in a single spatial mode well. To model our experiment, it is vital to include the effects arising from pulses propagating in two polarization modes simultaneously. Due to different group velocities in the two modes, the pulses only significantly overlap in time in the first $\approx 40$ cm of the fiber, and the last $\approx 40$ cm of the fiber. However, the interaction between the pulses via the cross phase modulation (XPM) effect cannot be neglected, especially at high pulse energy. The most pronounced effect of the XPM in the initial part of the fiber is that the central frequencies in the spectra of the two polarization modes undergo a transient change, resulting in a slight time delay difference at the end of the fiber. At higher powers, XPM can lead to soliton trapping, where the group velocities of the two pulses are equalized, and the spectra are symmetrically shifted. In our case, the soliton number is well below the trapping threshold value, nevertheless enough to misalign the pulses in time. It is important to eliminate this misalignment for the pulse to have a high degree of polarization. This group delay difference can be partially compensated by adjusting the energies of the two pulses, or by adjusting the lengths of the two halves of the fiber. The required adjustments are relatively small: the group delays can be made equal by rotating the input polarization by about 1°, corresponding to $\approx 7\%$ energy difference in the polarization modes, or by introducing the length difference in the fiber halves of about 3 cm. As mentioned above, in the experiment, the lengths of the fiber halves were slightly different precisely to compensate the XPM effect at the optimal pulse energy. Our modeling includes both the XPM effect and the difference in lengths between the two halves.

For each data point, we modeled 3000 Wigner trajectories in phase space using the stochastic nonlinear Schrödinger equation, this number of trajectories is enough for 0.1 dB precision. The results of the modeling are shown in Figure 7. The results are in good qualitative agreement with the experimental results, demonstrating better squeezing for shorter pulse duration, while the optimum power is larger for the longer pulses. In order to have a better quantitative agreement between the simulation and the experiment, one has to additionally include several effects which are difficult to estimate in the experiment from first principles. One of them is the GAWBS effect, most of which is canceled due to simultaneous co-propagation of the pulses. However, some residual effect is still present and can decrease squeezing, especially at low pulse energies. Additionally, not included in the modeling is the effect that at the splice point, each of the two polarization modes of the first half of the fiber may not couple only into one but a little bit and unintended also into the other orthogonal fiber mode of the second half of the fiber, which creates two low energy pulses before and after the main pulse and increases the noise power. In an attempt to explain this residual discrepancy, further simulations are underway.

7. Conclusion and Outlook

The novel scheme presented here led to a robust and conceptually simple generation of sizeable squeezing by using strictly copropagating beams. We note that in experiments high squeezing levels can be masked by a technical noise and instabilities of the experimental setup. The higher the squeezing the more precise the system must be tuned to measure this squeezing. The developed experimental setup provides enough passive stability, eliminating the need for active feedback and removing possible artifacts introduced by it. Also, in the proposed very symmetric fiber arrangement light travels essentially in the same spatial mode (only polarizations differ) throughout the whole system and thus experiences almost the same acoustic noise and other technical disturbances, thus such types of noise are canceled out almost completely. Even though the squeezing achieved in our system is slightly worse than record values for fibers, the system is very practical and consistently delivers significantly squeezed light for a long time. The next steps will be systematically exploring the experimental parameters further trying to find the optimum conditions for producing the best squeezing possible with this scheme. This includes variations of parameters — not only pulse energy and fiber length but also material parameters — modifying the type of nonlinear material used to fabricate the waveguide. One type of promising new material is silicon nitride forming wave guides integrated on a chip. The experimental exploration of this material platform in various geometries has already started. Ultrashort pulsed pump light, simulations had found that the eventual reduction in the amount of squeezing for higher pulse energies is caused by Raman noise. This is confirmed by the simulations reported here. However, recently it was found that in special fiber geometries the Raman noise may be significantly suppressed. It will be studied
whether this suppression can also be achieved under the conditions required for squeezing the quantum noise and whether the amount of squeezing can be further improved.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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