Quantum sensing encompasses highly promising techniques with diverse applications including noise-reduced imaging, super-resolution microscopy, as well as imaging and spectroscopy in challenging spectral ranges. These detection schemes use biphoton correlations to surpass classical limits or transfer information to different spectral ranges. Theoretical analysis is mostly confined to idealized conditions. Therefore, theoretical predictions and experimental results for the performance of quantum-sensing systems often diverge. This general simulation method that includes experimental imperfections bridges the gap between theory and experiment. A theoretical approach is developed and the capabilities are demonstrated with the simulation of aligned and misaligned quantum-imaging experiments. The results recreate the characteristics of the experimental data. The simulation results were further used to improve the obtained images in post-processing. As a simulation method for general quantum-sensing systems, this work provides a step toward powerful simulation tools for interactively exploring the design space and optimizing the experiment’s characteristics.

1. Introduction

Quantum sensing has become a rapidly evolving field with developments fueled by the outlook of applications that surpass classical limitations. These ranges from noise-reduced imaging over super-resolution microscopy to imaging and spectroscopy with undetected light as well as quantum holography. Especially one novel quantum-imaging technique—quantum imaging with undetected light (QIUL)—which has been recently experimentally demonstrated, provides many potential applications. Using QIUL, an image of an object is obtained without detecting the light that interacted with it. This concept has been adapted to applications in classical limitations. These ranges from noise-reduced imaging over super-resolution microscopy as well as imaging and spectroscopy in challenging spectral ranges. The principle of these measuring techniques is based on the quantum superposition of the biphoton states of two different sources. The light that interacts with the object is never detected. Meanwhile the light that does not interact with the object is used to form an image of that object. The registered image depends on the state of the undetected light due to the superposition of the biphoton states. This distinctive feature of QIUL allows for a probing wavelength at which detection is difficult, while detecting the image at a convenient wavelength.

Some properties of QIUL have been analyzed analytically and numerically. However, each work investigated only isolated aspects of QIUL, while a holistic description considering the interplay of various effects is still missing to date. A detailed understanding is of great importance for the assessment of limiting factors and the potential of this technique. A full model of the system further allows for the exploration of trade-offs between different imaging characteristics such as resolution and visibility. The availability of detailed simulations is becoming more relevant since applications are on the verge of a breakthrough, while their characteristic properties still need to be evaluated experimentally. Using simulations, the design process can be sped up as the system’s properties can be explored and optimized virtually.

In this article, we present and demonstrate a method for simulating the detected images of a QIUL setup. This method includes a full model of the biphoton sources and the optical system. With this, a large range of experimental setups including their misaligned states can be simulated. We further present an approximative variant of the method, which speeds up the computation times substantially. For this variant, the model of biphoton sources is simplified. The approximative variant is still applicable to a large range of experimental setups but is limited to fewer types of misalignments. We demonstrate our method by simulating detector images and imaging properties of a real experimental setup. With this, we present a simulation suite enabling the virtual analysis of quantum-sensing experiments.

QIUL schemes with a Mach–Zehnder geometry (Figure 1) are driven by two coherently pumped identical nonlinear crystals (NL1 and NL2), which produce biphoton states consisting of a signal (s) and an idler (i) photon. Schemes with a Michelson geometry use one nonlinear crystal through which the pump laser passes twice. We treat the first and second pass as two...
sources and denote them with NL1 and NL2 to keep the notation consistent. We assume the power of the laser to be small enough, such that the nonlinear influence of stimulated emission may be neglected. The signal parts of the biphoton states emitted from each source (yellow paths) are superposed and subsequently detected with a camera. The idler part (red paths) emitted by NL1 is propagated through NL2 and aligned with the corresponding beam emitted by NL2. In an ideal setup the probability amplitudes and modes emitted by NL1 and NL2 are identical. Therefore, the idler states are indistinguishable and no information about the emitting source can be obtained in the detector plane. Due to the momentum correlation between photons s and i, the observed interference on the idler path even though only signal photons are detected. To measure an object’s properties, it is placed in the path of the undetected idler beam between the two crystals. The transmission coefficient and the phase introduced by the object can then be reconstructed from the detected image.

2. Theory of Quantum Sensing

Our simulation model consists of three parts: the source model, the propagation model, and the detection model. The source model describes the quantum states created by the biphoton sources. The propagation model calculates the propagation of these states through the optical system. The detection part evaluates the interference of the two paths and the resulting signal in the detector plane. In the following, we will limit ourselves to the description of QIUL setups in a far-field configuration.

The source model is used for the calculation of the transition amplitude \( g(k_s, k_i) \) for each pair of photon momenta \( k_s \) (signal) and \( k_i \) (idler). The quantum state of light generated by the sources NL1 and NL2 is given as

\[
|\psi_{NL1/NL2}\rangle = \int dk_s dk_i|g_{s/i}(k_s, k_i)|k_s, k_i\rangle
\]

where \( g_{s/i}(k_s, k_i) \) are the transition amplitudes for the nonlinear crystals NL1 and NL2, respectively. We omit the polarization component of the biphoton state for simplicity. Many biphoton sources used for QIUL emit mainly one combination of photon polarizations.

Next we consider the propagation, which encompasses the change of momenta and positions, losses, and phase shifts of the biphoton states. We model losses due to propagation and from the imaged object as beam splitters with transmittance \( t \) and a phase shift \( \phi \) such that they can be described by the transformation \( \hat{\rho} \rightarrow t e^{i\phi} \hat{\rho} + (1-t) \hat{I}_\text{loss} \). Here, \( \hat{\rho} \) are the photon creation operators and \( \hat{I}_\text{loss} \) represents all losses along a beam path or from the object. In general, the transmittances and phase shifts depend on the photon momenta. We omit this dependence in the following equations for the sake of readability. The propagation of the states \( |\psi_{NL1/NL2}\rangle \) through the beam paths from a source plane to the detector plane is modeled by the transformation of the photon momenta \( \hat{k}_m \rightarrow \hat{k}'_m = h_m(k_m) \) for \( m = i1, i2, s1, s2 \). Here \( h_m \) is a transformation function modeling the changed photon momenta after the propagation from the source planes P1 and P2 to the detector plane D. The definition of the planes is shown in Figure 2.

In an ideal setup, a plane wave emerging from one of the crystals is focused onto a point on the detector. This point \( \rho(h_{i1}(k_{i1}))/2 \) depends on the momentum vector \( k_{i1} \) and a point on the object \( \rho(h_{s1}(k_{s1})) \) (Figure 2b). For a more realistic setup, these assumptions do not hold as the components are not perfect and further might be misaligned. In order to still have a momentum-to-point relation, we make the assumption that the spatial extent of the sources can be neglected.

With this, we can establish a relation between the photons from the two sources (Figure 2a,c). Figure 2 illustrates these relations for a Mach–Zehnder setup as well as the employed notation. A biphoton state emitted from NL1 with signal momentum...
\( k_i \) is detected at the point \( \rho(h_{s1}(k_i)) \) on the detector. For a biphoton state from NL2 to be detected at the same point the signal part needs to have the momentum \( k_i' \) in the source plane NL2, where \( k_i' \) is defined as the momentum that fulfills \( \rho(h_{s1}(k_i')) = \rho(h_{s1}(k_i)) \). We can establish an analogous relation for the idler photons. With these relations from the propagation model we can formulate the detection model. The quantum state at the detector plane can be expressed as

\[
\Psi_d = \int d k_i \int d k_i' \Gamma_s(g(k_i, k_i') t_{s1} t_{s2} e^{i \Phi(k_i') \Delta(\rho(k_i'))}) + g(k_i, k_i') t_{s1} t_{s2} e^{i \Phi(k_i') \Delta(\rho(k_i'))} + g(k_i', k_i) t_{s1} t_{s2} e^{i \Phi(k_i') \Delta(\rho(k_i'))} \psi_d \]

where \( \Delta \Phi_o \) denote the phase shifts from the propagation through the various optical paths, which are provided in detail in Equations (S4)–(S7). Supporting Information, \( t_s \) is the transmittance of the imaged object, \( t_{s1}/t_{s2} \) are the transmittances of the signal paths between source and detector planes and \( t_t \) is the transmittance of the idler path between the two source planes. The first three terms describe the biphoton states emitted from crystal NL1. Starting with the case where both photons are transmitted through the system and then only the signal where only signal or only idler photons are transmitted. The fourth term describes biphotons from the second crystal. We omitted further terms, which do not contribute to the measured signal, such as idler losses after NL2.

From the state at the detector we obtain the count rate for a point on the detector plane as

\[
\Gamma^s(\rho(k_i')) = \left| \langle \hat{a}^\dagger(k_i') + \hat{a}^\dagger(k_i') \rangle \right| \psi_d \right| \psi_d \rangle (3)
\]

\[
= \int d k_i \left[ g(k_i, k_i') t_{s1} t_{s2} + g(k_i', k_i) t_{s1} t_{s2} \pm 2 g(k_i, k_i) g(k_i', k_i') t_{s1} t_{s2} t_t \cos(\Delta \Phi) \right]
\]

where \( \Delta \Phi = \Phi_o - \Delta \Phi_i \) is the phase difference of biphoton states created in NL1 and NL2. In general, the phase terms depend on the photon momenta and therefore, the cosine term cannot be extracted from the integral. The different signs of the third term stem from the \( \pi \) phase shift the beam splitter introduces to one of its output ports. To obtain the count rate for a detector pixel we integrate \( \Gamma^s \) over the area covered by this pixel and multiply with the detector efficiency.

From the measurements at the two outputs (see Figure 1), we can calculate the pointwise visibility, which gives an approximation of the optical properties of the object in the idler path

\[
V(\rho(k_i')) = \left| \Gamma^s(\rho(k_i')) - \Gamma^i(\rho(k_i')) \right| \left| \Gamma^s(\rho(k_i')) + \Gamma^i(\rho(k_i')) \right|
\]

where we have assumed identical imaging systems for the two measurements. In this general case, the relation of this quantity and the object properties is not straightforward. For an idealized setup with perfect momentum correlation, the idler momentum integrals vanish, which yields \( V \propto t_t \cos(\Phi) \), where \( \Phi \) is the phase shift introduced by the object. We can make some approximations to simplify Equation (6) while still retaining important properties of the system. For this we assume the crystals to be identical (\( g = g_s = g_i \), constant, and equal losses in the optical paths (\( t_s = t_{s1} = t_{s2} \)), vanishing phases (\( \Delta \Phi = \Phi \)), and an optical system that ensures \( k_{s1} = k_{i1} = k_{i2} \). This allows us to reduce Equation (6) to

\[
V(\rho(k_i')) = \frac{\int d k_i g(k_i, k_i') t_{s1} t_{s2} t_t \cos(\Phi)}{\int d k_i g(k_i, k_i') t_{s1} t_{s2}}
\]

where only the transition probabilities and object properties \( t_t \) and \( \Phi \) depend on the photon momenta.

We further simplify and consider biphoton sources where the normalized transition probabilities \( \tilde{g} = g(k, k') (\int d k_i g(k, k') t_{s1} t_{s2})^{-1} \) depend only on the difference in \( k \) and \( k_i \) and that is, \( \tilde{g} = \tilde{g}(k - k_i) \). In the case of a purely absorbive object (\( \Phi = 0 \)) this reduces Equation (7) to a convolution of the object’s transmittance with the \( \tilde{g} \) kernel

\[
V(\rho(k_i')) = t_t \int d k_i \tilde{g}(k - k_i) t_t \rho(\tilde{g}(k_i'))
\]

where the dependence of the object transmittance is now explicitly given. Due to the constant convolution kernel this approach yields a computationally fast method for calculating the measurement for any object. From this, properties of the imaging setup such as resolution limit and maximum visibility can be inferred. The employed assumption can readily be applied if the region of interest is the center of the spots in the detector plane or when the relative noise at lower count rates can be neglected. The assumption of a constant kernel means that the simulated count rates are constant across the detector plane, meaning no information is gained about the field of view. Further the accuracy of the images is reduced for a large spread of signal or idler emission angles. The assumption of vanishing phases can be relaxed giving a more general case where the convolution kernel becomes shift variant as it also contains the cosine term. Including the signal \( \varphi_s \) and idler phases \( \varphi_i \) allows for the emulation of misalignments, such as transversally shifted lenses in the two optical arms. An improvement in computational efficiency is retained as long as \( \tilde{g} \) needs to be evaluated only sparsely. Both the quasi-Monte Carlo simulation and the convolution approximation can be extended to a broader spectral range by integrating over \( k_i \) as well.

The insight, that the measured image can be seen as a convolution of the object combined with a way to calculate the convolution kernel, paves the way for using established deconvolution and image reconstruction techniques. Using these techniques in the post-processing of the detected images allows to improve their quality without any improvements in the detection system. Applied correctly, deconvolution techniques provide a more accurate approximation of the inferred object properties. To demonstrate this, we use the Richardson–Lucy algorithm\(^{25,26}\)
deconvolve the simulated measurement results with the convolution kernel $\hat{g}$.

3. Implementation

To demonstrate the capabilities of our simulation methods, we model a far-field Mach–Zehnder interferometer setup presented in Ref. [10]. The setup’s sources create biphoton states with central wavelengths $\lambda_i = 810$ nm and $\lambda_s = 1550$ nm. A detailed account of the model of the setup is given in the Supporting Information.

To describe the biphoton states produced by the two spontaneous parametric downconversion (SPDC) sources NL1 and NL2 we use a highly accurate and general model for predicting absolute photon rates based on Ref. [27]. This sophisticated model takes many of the material properties into account, such as the wavelength dependence of refractive indices and nonlinear susceptibility yielding an accurate and complex SPDC model that needs to be evaluated numerically. The employed model is outlined in the Supporting Information. Note that the approximations that have been made for the derivation of the SPDC model do not limit the generality of the presented method, as it can be substituted with a different source model.

The magnification of the setup depends on the wavelengths of signal and idler,$^{[8,22]}$ it can be approximated by

$$M = \frac{f_o f_s}{f_i f_s}$$

(9)

where $f_i$ and $f_o$ are the focal lengths of lenses $L_{i1/2}$ and $L_o$ in Figure 2, respectively. In general, the magnification is different along the crystal axis due to the birefringence of many nonlinear crystals. For the setup presented in this paper, these differences can be neglected.

The transformation functions $h_\omega$ are modeled using geometrical optics. The momentum $k$ and position $\rho$ in the plane of interest is evaluated by propagating a ray defined by the photon momentum to the corresponding plane. This is used to determine the position on the object and detector, as well as the photon momenta in the plane of the second source $k_{\text{out}}'$. The phase terms are determined from the optical path lengths $L_i$ as $\phi_\omega = \omega L_i c^{-1}$. For the aligned interferometer we assume that only the phase shift from the object is relevant, that is, $\Delta \phi = \phi_s$. We further assume that no losses occur in the optical paths ($t_i = t_s = 1$), as these are either constant factors, which reduce the visibility. Or they are complex functions, which would diminish the clarity of the demonstration of our simulation method. For a full simulation of the QIUL setup we evaluate Equation (3) over the detector area using a quasi-Monte Carlo integration scheme. For the convolution variant, we evaluate the normalized transition probabilities $\hat{g}(k_i - k_s)$ for the collinear $k_i$ defined by the optical axis of the system and the central signal wavelength of the setup $\lambda_i$. This is used to calculate the convolution of the object given in Equation (8).

The computational expense of evaluating $\hat{g}$ is equivalent to the evaluation of one pixel on the detector, reducing the theoretical computation time by six orders of magnitude for this setup. In practice, the computation time depends largely on the numerical accuracy one wants to achieve. In the presented case the required computation time for a smooth collinear kernel $\hat{g}$ is around 1 s on a single thread. This is the main cost of the convolution variant. The remaining computations are matrix multiplications done in sub-microsecond times. For our simulated 1000 $\times$ 1000-pixel detectors the resulting computation time would be scaled by the number of pixels giving 278 h. However, the kernel needs to be much smoother than our simulated image, such that we can reduce the numerical accuracy for the full simulation method. For the low count rate pixels at the outside of the detector the accuracy can be reduced even more. For the presented results this achieved a speedup by a factor of 40, giving a single thread computation time of 7 h for the full simulation results, which include $\Gamma^+$, $\Gamma^-$, and the visibility.

4. Numerical Results and Discussion

We simulate the detector images with the absorption object shown in Figure 3. It measures 4 $\times$ 4 mm$^2$, has three horizontal, 200 $\mu$m wide bars with the same distance between them, and two vertical bars of the same width but separated by 1000 $\mu$m. The pump beam waist used for this simulation is 300 $\mu$m. The results of the simulated detector images and measurement of the transmittance of a test object are shown in Figure 4. The results for the detector count rates $\Gamma^+$ and $\Gamma^-$ are shown in Figure 4a,b, respectively. The two simulated images show the expected behavior, where the sum of both images gives the intensity profile of the signal radiation without distinctive features, whereas the difference shows an image of the object. These figures also show the spot size of the signal radiation. The noise visible in the simulated detector images is a numerical artifact, which is caused by the finite number of points we evaluated. The noise is perfectly correlated between the two images such that the resulting pointwise visibility shows no artifacts from this noise. Figure 4c shows the measured pointwise visibility of the object, which is defined by Equation (5). To demonstrate more realistic conditions, we add Gaussian noise with a standard deviation of 50 counts to the left half of the detector images for the calculation of this image. We clip values below 0 and above 1. The right half is free from artificial noise to illustrate the influence of this added noise. The resulting measured visibility shows a smeared out image of the object. The visibility in the noise-free half of
Figure 4. Simulation results. Simulated measurements of the transmission object shown in Figure 3. a,b) Detector images for the destructive (Γ−) and constructive (Γ+) configuration. The noise stems from the finite sampling rate and is perfectly correlated between the two images. c) The resulting measured transmittance. For the left half Gaussian noise was added to the detector images, the right half is free from artificial noise. d) Constructive detector image for the misaligned setup. The lens misalignment leads to vertical stripes in the detector plane. The top panel shows simulated and theoretical modulation from the phase shift at $y = 50$. The visibility does not decrease toward the outer parts of the features. In the noisy half of the image, the visibility ranges from 0.1 to 1 and the noise is more prominent in the corners where the count rate is lower. The measured distance of the centers of the vertical bars is 1255 µm. The distance on the object is 1200 µm (see Figure 3), which gives a magnification value of 1.046, in agreement with the theoretical prediction from Equation (9) ($M = 1.045$). The accuracy of the measured magnification is limited by the detector pixel size.

In real experimental setups, noise is not the only issue. Even with included noise, they will always fall short of this ideal setup. As components have imperfections and cannot be aligned perfectly, our model needs to be able to reflect these effects. Due to the flexible propagation model, this is possible. To demonstrate our method’s capabilities for misaligned systems, we shift the idler lens $L_{i1}$ in front of the object by $d = 0.3$ mm transversally with respect to the optical axis as shown in Figure 1. This introduces a phase shift, which depends on the emission angle of the idler photons. Figure 4d shows the introduced vertical stripes in the simulated detector images as one would expect from misaligning an interferometer. The width of the stripes depends on the magnification and the misalignment. An analytical expression for the phase shift in the detector plane is derived in Equation (S11). Supporting Information. The analytical and simulated results are shown in the top panel of Figure 4d. Our simulated stripe pattern matches the theoretical predicitions closely. The pointwise visibility in this setup is decreased to the range from 0 to 0.64 due to the phase variation in the idler states.

We further calculated the resolution limit for both setups presented by Fuenzalida et al.[10] numerically (see Supporting Information) for an ideal version of the setups and with a reduced maximum visibility to compare with the measured results. Our results, shown in Figure 5, follow the same characteristic curves as the measured results for both experimental setups. The resolution limit of the ideal setup is consistently $\approx 17\%$ smaller. This is to be expected when comparing an ideal with a real setup. The reduced visibility explains the experimental data well. The maximum visibility minimizing the root-mean-square error (RMSE) with the experimental data is 50% and 39% for setups 1 and 2, respectively. The accuracy of the experimental results is limited not only by measurement accuracy, but also because the used test target only provides discrete slit widths. The simulated results provide continuously calculated values. Reasons for the reduced visibility are the common difficulties in real experiments:
imperfect overlap of the beam paths, losses, noise, and others. However, higher maximum visibilities of 77% have been achieved for similar setups\cite{1,8} such that other effects, which reduce the resolution but not maximum visibility, are likely to be important here. Possible causes are imperfect imaging in the signal path, as well as imaging errors that increase the spread of the idlers in the object plane. Lens and mirror misalignments, and spherical aberrations are potential causes for this effect. Our ideal results present a theoretical limit to the achievable resolution for these setups and show that these experimental realizations might still be improved. A detailed analysis of the experimental setups can be performed using our simulation method. This allows the identification of sensitive parts and limiting factors, which can be used to improve the setups.

With these examples we have demonstrated the capability and versatility of the presented simulation method. Under certain conditions we can formulate the pointwise visibility as a convolution, which leads to a huge speedup of the simulation times while still gives accurate results. To demonstrate this, we change the beam waist to 200 µm and use an absorption object that consists of three vertical slits with transmittance $t = 1$. The width and distance between the slits is 128 µm, which is the resolution limit for the setup in this configuration. A horizontal cut at the center ($y = 500$) of the detector is shown in Figure 6. The figure shows the results for the full simulation and the convolution method. The convolution method yields an accurate approximation of the fully simulated image. The maximum difference in visibility over the shown area is 0.007, showing that this method provides a fast and accurate approximation for the full simulation results. An extension of this method to phase objects and misaligned setups and the corresponding simulations are shown in the Supporting Information. A downside of this method is that the limited spot size is not considered. For system characteristics such as visibility and resolution limit the convolution method provides a fast calculation method that enables the exploration of the influence of different parameters and the optimization of setups.

The convolution kernel used for the convolution variant can also be used to improve the information we obtain from the two measurements. For this we apply the Richardson–Lucy deconvolution with the collinear convolution kernel $\hat{g}$ to the simulated visibility shown in Figure 4c. The result after 50 iterations, shown in Figure 7, is a much sharper image with narrower edges and an increased contrast, especially in the center. Outside of the beam spot the large relative noise leads to large artifacts. We therefore limit our analysis to a box defined by $x \in [100, 900]$ and $y \in [300, 700]$, which cuts off the parts where noise is dominant. In this box, the deconvolution algorithm introduces only minor artifacts. With a maximum amplitude of 0.05, they are barely visible in the figure. In this area, the noise leads to minor distortions. The addition of noise does negligibly increase the amplitude of the artifacts compared to the noise-free half. To compare the deconvolution to the regular simulation results, we calculate the RMSE to the real object for both methods. The deconvolution method improves the RMSE in the noisy and noise-free half by 37% and 35%, respectively. The range for the pointwise visibility in the center of the image is improved from [0.1, 0.8] to [0, 1], which is the maximum achievable contrast. In the noise-free half, the maximum improvement for a single pixel is 0.44, the mean
improvement on this side is 0.1. To quantify the improvement in the sharpness, we have calculated the resolution limits including the deconvolution step. Compared to the simulations without deconvolution, we found a consistent improvement of 13% across a large range of beam waists.

5. Conclusion

We have presented and demonstrated a general method for simulating quantum imaging with undetected light. These simulations enable the characterization of QIUL systems in the design phase. We presented a method for full-fledged simulations of QIUL systems, which allows analyzing a large range of setups in full detail, including the influence of many misalignments. This method is suitable for the simulation of the actual detector images of a setup. The convolution approximation provides a trade-off between computation time and accuracy and also a fast way to evaluate characteristics of a setup with slightly limited options for misalignments. The numerical simulations enable the identification of limiting factors of QIUL systems. The fast computation times of the convolution approximation allow for an interactive exploration of the design space and optimization of the imaging characteristics, and can enable the development of adaptive control systems—both invaluable tools for improving applications based on QIUL. Both methods yield similar results for perfect imaging systems. A comparison with analytical and experimental results shows that the simulation results show realistic benchmarks of experimental setups.

We further demonstrated the improvement of imaging characteristics by deconvolution techniques. In our simulation experiment, we showed that the quality of an image can be improved greatly by applying this technique.

Our results demonstrate the principle of the methods. Using more accurate optical models to reproduce the images from experimental setups is subject of further research. The convolution technique can also be improved. By incorporating multiple convolution kernels, it is possible to get a better approximation for the variation in different detector regions, allowing for an estimation of the absolute count rate as well. Further work is also possible in applying the deconvolutional technique to real experimental setups and data. This requires an accurate model of the setup and its imperfections. Using a deconvolution algorithm for shift-variant kernels allows adding the phase information to the deconvolution method, which can improve the image further, since in real setups phase errors always occur.

The presented approach can also be applied to a wide range of other experimental setups. We have presented an approach specifically for collinear spectroscopy experiments before.[18] The application to a Michelson geometry or a near-field configuration can be realized by adapting the transfer functions[19] or by using position-space operators instead of momentum-space operators,[20] respectively. The simulation method we present can be further extended to include the spatial component of the biphoton sources. However, this requires a different source model and is beyond the scope of this proof-of-concept paper. At the current stage, the presented model and methods already provide the necessary basis for the simulation of experiments and applications based on quantum imaging with undetected light and enables obtaining improved images.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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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.

**Keywords**

imaging with undetected light, imaging with undetected photons, nonlinear interferometers, quantum sensing

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