

Impact of polarization mode dispersion on entangled photon distribution

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(Received 9 April 2025; accepted 20 August 2025; published 22 September 2025)

The polarization mode dispersion (PMD) in optical fibers poses a major challenge for maintaining the fidelity of quantum states for quantum communications. In this work, a comprehensive model linking the probability of quantum measurement errors (infidelity) to PMD is developed and validated by experimental measurements of differential group delay and quantum bit error rate (QBER). Our research proposes effective methods to mitigate PMD effects for broadband entangled photons and evaluates the impact of higher-order PMD effects. The model provides an experimentally verified framework for the optimization of commercial quantum key distribution systems in deployed fiber-optic lines.

DOI: [10.1103/1217-b98w](https://doi.org/10.1103/1217-b98w)

I. INTRODUCTION

Quantum communication is a rapidly developing field that focuses on facilitating communication between quantum computers [1–3] or applying the principles of quantum mechanics to cryptography in the technology of quantum key distribution (QKD) [4–6]. Like its classical counterpart, the communication process is often facilitated by fiber optics, particularly within metropolitan-area networks [7]. Similarly, fiber-based quantum communication is affected by chromatic dispersion and polarization mode dispersion (PMD), both of which must be managed to ensure successful transmission [8].

PMD occurs in optical fibers, causing wavelength-dependent polarization transformations of light as it travels through the fiber. This phenomenon results from the residual birefringence in the fiber induced by the manufacturing imperfections and stress. In an ideal single-mode fiber, light propagates without any depolarization, while in a real-world situation, we observe varying phase shifts for different polarization modes at different wavelengths [9].

In this work, we study the depolarization effects induced by PMD and caused by the finite spectral width of the optical signal. This is directly relevant to many applications of quantum technologies, especially those involving entangled photon states. For better demonstration, we used a graphical approach, visualizing the state of light on the Poincaré sphere.

PMD in single-mode fibers manifests as a change in the output polarization state with a change in the wavelength, while the input polarization remains constant. Figure 1(a) shows an exemplary output polarization trajectory on the surface of the Poincaré sphere measured for an installed 30-km-long fiber over a 100-nm bandwidth.

If classical communication uses the polarization degree of freedom, two orthogonal states usually suffice; they are best chosen as the principal states of polarization (PSPs), the two orthogonal eigenpolarization modes of the fiber that undergo no polarization transformation at a given wavelength. In the context of quantum communications, the use of just two orthogonal polarization states is generally insufficient, which exacerbates the challenges brought by the PMD phenomena. First, one must use superpositions of orthogonally polarized states [10] in order to achieve an advantage over classical communications.

Second, the practical generation of nonclassical light, such as spontaneous parametric down-conversion (SPDC), often results in much more broadband signals than generated by conventional laser sources. This is especially the case for the most efficient type-0 process, known for its relatively broad spectrum [see Fig. 1(b)]. Thus, maintaining the fidelity of quantum states becomes a significant challenge that directly affects the quality of QKD and other applications of quantum communications.

In our study, we distribute bipartite entangled states

$$|\psi\rangle = \frac{|HH\rangle + |VV\rangle}{\sqrt{2}}, \quad (1)$$

defined in terms of the H (horizontal) and V (vertical) basis states, which guarantee fully correlated results, provided the photon polarizations are measured in the same basis. Tracing out one of the particles from the corresponding bipartite density matrix yields $I/2$ that corresponds to the fully mixed or unpolarized single-photon state. We assume that

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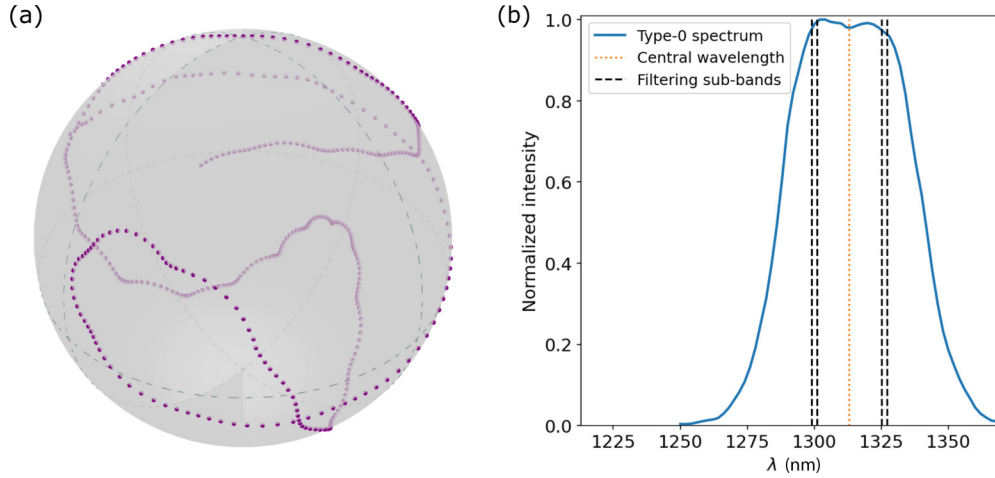


FIG. 1. Necessity of narrow subband filtering due to PMD. (a) Observed polarization trajectory upon propagation through 30 km of typical telecom fiber, measured over the range of 1260–1360 nm in steps of 0.25 nm. (b) Example of a broadband type-0 SPDC spectrum (experimentally measured), produced by 25 mm of periodically poled lithium niobate crystal with a poling period of 12.83 μm . The pumping wavelength is 656.5 nm.

the distributed entanglement is later used in the most popular entanglement based protocol, the BBM92 QKD protocol [4,5]; however, the main results are directly applicable to other possible entanglement utilization.

The most direct way to decrease PMD-induced distortions and improve correlations is to reduce the spectral width of the source using narrow-band filtering before transmitting the light into the fiber. Figure 1(b) shows an example of filtering distant wavelengths, which is convenient for separating entangled photons by channels. However, such filtering directly affects the brightness of the source, creating a trade-off between the brightness of the transmitted light and the observed quantum bit error rate (QBER). Optimization of the system thus requires a model linking the channel parameters and the bandwidth of the signal to the level of distortion experienced in BBM92-type measurements. The most common parameter that describes PMD in a fiber channel is the differential group delay (DGD) [9]—the difference in the transit time for light launched into two PSP modes. Our main goal is to find a simple relation connecting the measurement error probability to the filtering bandwidth and the DGD of the channel.

The effects of various types of optical dispersion in fibers on QKD applications present several challenges and were studied previously. Nonlocal dispersion compensation has been proposed [11] and experimentally validated [12,13] to address the chromatic dispersion.

Polarization mode dispersion was also extensively studied both theoretically [14] and experimentally [15–17]. However, all of these works used a simplified and limiting PMD model, in which PSPs and DGD are wavelength independent and known *a priori*. Thus, complex polarization transformations associated with real-world PMD were not addressed. Likewise, the experimental papers specifically studied the effects of DGD-induced temporal separation between polarization components under the assumption of a pulsed (broadband) SPDC pump, which does not apply to the much more common case of cw or narrow-band pumping. Third, the experimental methods of study in all cases included a full tomography of quantum states, which is a complex and time-consuming

process. For example, in [15] it took 1 h at a repetition rate of 45 MHz, which is entirely unfeasible for practical communication lines, where polarizations fluctuate over a timescale of minutes.

Another relevant experimental study [18] and its theoretical generalization [19] specifically focused on the single-wavelength prepare-and-measure scheme. The polarization control was performed based on classical reference signals, which are separated from the quantum one either in time or in wavelength. In this case, PMD results in the decorrelation between the reference and the quantum signal. However, being essentially a single wavelength, the quantum signal does not experience any decoherence by itself, so these previous results do not address the effect of decoherence studied in the present work.

This paper is organized as follows. In Sec. II, we present a graphical approach linking the measurement error probability to the PMD. Then Sec. III provides experimental validation through DGD measurements and QBER analysis in a real QKD system. Finally, in Sec. IV, we propose methods to mitigate PMD effects for broadband entanglement-based QKD and assess the impact of higher-order PMD effects.

II. MODEL DESCRIPTION

The transformation of the output polarization state s_{out} in a fiber can be described by the PMD vector $\vec{\Omega} = \Delta\tau \vec{p}_1$, where $\Delta\tau$ and $\vec{p}_1$ are the DGD and PSP vector, respectively [20]. When the light frequency changes from ω_1 to ω_2 , the output polarization state rotates around the PMD vector, as shown in Fig. 2(a). The first-order PMD is defined by the linear relation

$$\Delta\theta = \Delta\tau(\omega_2 - \omega_1) \quad (2)$$

between the rotation angle $\Delta\theta$ and the DGD, where the PMD vector is assumed to remain constant across all frequencies in the given range. In contrast, higher orders of PMD define variations in the length and orientation of the PMD vector with changes in frequency [20]. Thus, the first-order PMD describes a regular circular rotation around $\vec{\Omega}$

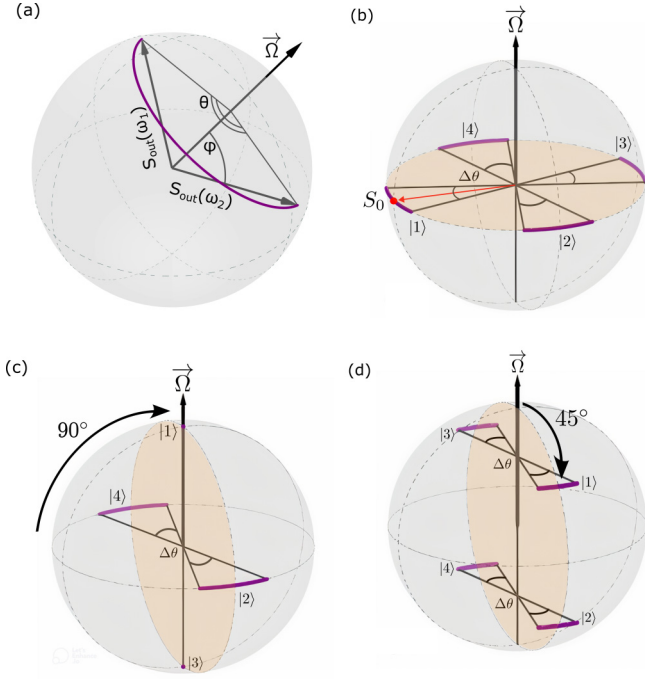


FIG. 2. Polarization trajectories on the Poincaré sphere with wavelength variation. The labels $|1\rangle$ – $|4\rangle$ correspond to the quantum states belonging to two mutually unbiased measurement bases used in the BBM92 protocol. After the states propagate through the fiber, PMD causes each one to sweep out a trajectory on the Poincaré sphere. (a) The first-order PMD: Output polarization rotates around the PMD vector. (b) The largest distortion case, where the PMD vector is orthogonal to the four-state circle plane. (c) The PMD vector lies in the four-state circle plane coinciding with one of the basis, in which no distortions are observed. (d) A symmetrized case, where the PMD vector lies in the four-state circle plane.

on the Poincaré sphere. The actual trajectory of polarization transformation from Fig. 1(a) can be matched by assuming frequency-dependent parameters $\Delta\tau(\omega)$ and $\bar{p}_1(\omega)$ and the resulting $\vec{\Omega}(\omega)$ [21]. Longer trajectories of an output polarization state on the Poincaré sphere correspond to larger distortions caused by the PMD.

In the context of the BBM92 protocol, the photon source creates an entangled state (1), where each component is uniformly distributed across the Poincaré sphere. At the receivers' locations, the components are randomly measured in one of the two mutually unbiased bases, for example, in horizontal-vertical and diagonal-antidiagonal bases. These four states define a great circle on the Poincaré sphere, which we will call a four-state circle below. Propagation over the fiber effectively modifies these basis states, including the effects of the wavelength-dependent PMD. All polarization changes in the fiber are subject to fluctuations over time as a result of environmental changes.

For simplicity, we start with the first-order PMD, which is an accurate approximation if we consider small enough trajectory patches. An important consideration is that the four-state circle, formed by the measurement basis vectors, can have different orientations with respect to the PMD vector. The longest total trajectory corresponds to the PMD vector

oriented perpendicularly to the four-state circle [Fig. 2(b)]. However, it is also possible to reduce the PMD-induced distortion by choosing measurement bases such that the four-state circle plane comprises the PMD vector. If a basis coincides with the PSP vectors, the corresponding trajectories reduce to single points, so only the opposite basis contributes to PMD-caused measurement errors, as shown in Fig. 2(c). Another notable configuration is a symmetrical one, as depicted in Fig. 2(d), where the PMD vector lies in the four-state circle plane between two adjacent basis states.

Consider a trajectory L on the Poincaré sphere created by broadband light with a spectrum evenly distributed within a bandwidth $\Delta\lambda$. When we measure the output polarization projecting it onto a chosen state $|s_0\rangle$, the intensity is directly proportional to the integral of the corresponding amplitude modulus squared over all polarization states within the trajectory L :

$$I \propto \int_L |\langle s(\lambda)|s_0\rangle|^2 d\lambda. \quad (3)$$

In the case of single-photon measurements in the basis $\{|s_0, s_{0_orthogonal}\rangle\}$, the measurement error probability p_e can be determined using

$$p_e = 1 - \frac{1}{\Delta\lambda_L} \int_L |\langle s(\lambda)|s_0\rangle|^2 d\lambda, \quad (4)$$

which we refer to below as a “trajectory integration” (considering a flat biphoton spectrum within $\Delta\lambda_L$). It can be understood as the PMD contribution to QBER for a particular state measurement. It is easy to show that p_e is, in fact, the infidelity [22] between the median pure state $\rho_0 = |s_0\rangle\langle s_0|$ and the resulting density matrix

$$\rho(\Delta\lambda) = \frac{1}{\Delta\lambda_L} \int_L |s(\lambda)\rangle\langle s(\lambda)| d\lambda, \quad (5)$$

where infidelity is defined as $1 - F(\rho_0, \rho(\Delta\lambda)) = 1 - [\text{tr}(\sqrt{\rho_0\rho(\Delta\lambda)})]^2$ [23].

Now we consider a relatively small arc of the circle formed by the angle $\Delta\theta$ corresponding to the filtering bandwidth $\Delta\lambda$. Given a uniform spectral distribution, we choose s_0 to be the central point of the arc in Fig. 2(b), so the overall error probability is minimized. The resulting infidelity is obtained through integration over all wavelengths:

$$\begin{aligned} p_e &= 1 - \frac{1}{\Delta\theta} \int_{-\Delta\theta/2}^{\Delta\theta/2} \left(1 - \sin^2\varphi \sin^2\frac{\theta}{2}\right) d\theta \\ &= \frac{\sin^2\varphi}{2} \left[1 - \text{sinc}\frac{\Delta\theta}{2}\right], \end{aligned} \quad (6)$$

where φ is an angle between the polarization state and the PMD vector $\vec{\Omega}$ [Fig. 2(a)]. It has to be mentioned here that the sinc shape of the infidelity is effectively the Fourier transform of the assumed rectangular signal spectrum. Gaussian spectral distribution would result in a Gaussian infidelity shape and so on.

For the most practically interesting case of relatively small p_e this can be further simplified using Taylor expansion in powers of $\Delta\theta$ to get a useful relation:

$$p_e \approx \sin^2\varphi \frac{(\Delta\theta)^2}{48}. \quad (7)$$

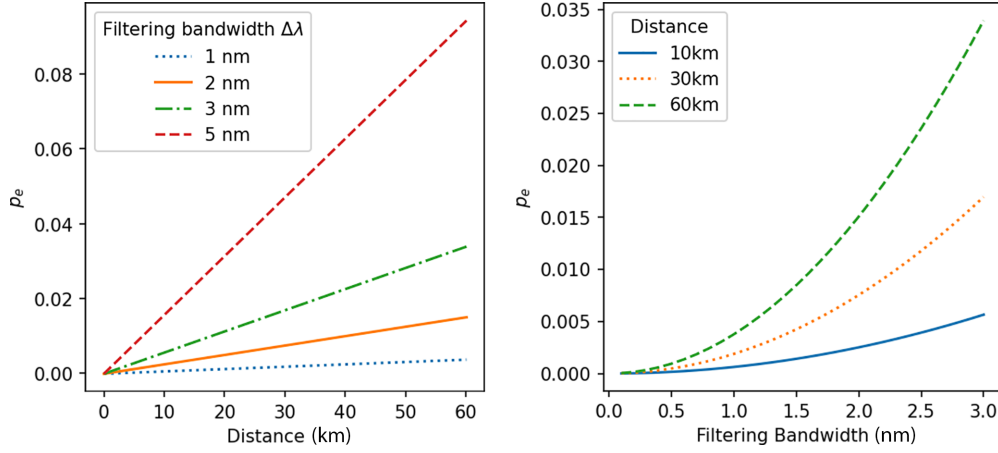


FIG. 3. Expected infidelity p_e vs fiber link distance (left) and the bandwidth of filtering (right). For the calculation (8), we used the PMD coefficient $\text{PMD}_Q = 0.05 \text{ ps}/\sqrt{\text{km}}$.

From a known DGD value, for a given $\Delta\lambda$, we can find $\Delta\theta$ using Eq. (2), which is now directly related to the expected p_e . As a result, we relate the effective infidelity to both the filtering bandwidth and the QKD distance; Fig. 3 shows typical estimates based on the statistical PMD model. As the PMD effect in single-mode optical fibers is a statistical phenomenon—each link’s DGD follows a Maxwellian distribution that arises from the many independent birefringence segments—the mean DGD scales with the square root of the distance L [20],

$$\langle \Delta\tau \rangle = \text{PMD}_Q \sqrt{L}, \quad (8)$$

where we used the experimentally obtained coefficient $\text{PMD}_Q = 0.05 \text{ ps}/\sqrt{\text{km}}$, typical for our fibers. Thus, the relationship between the propagation distance and p_e is linear, while the dependence on the filtering bandwidth exhibits a quadratic behavior.

III. EXPERIMENTAL VALIDATION

To estimate the actual PMD-induced signal degradation in a real-life scenario, we exploit two different methods.

First-principles approach. This estimation is based on the actually measured polarization trajectory on the Poincaré sphere under varying input wavelength. For a certain signal bandwidth $\Delta\lambda$ we find the corresponding trajectory patch on the Poincaré sphere. Assuming the optimal alignment of the measurement basis, we choose the measurement state s_0 to be the central point of this patch. As can be seen in Fig. 2(b), the measurement S_0 is affected by the PMD distortion of the original state $|1\rangle$. Infidelity is calculated through numerical integration (4) along the patch. For a longer trajectory, as illustrated in Fig. 1(a), the patch is rolled along the trajectory, and the rolling integration yields infidelity as a function of wavelength for a given $\Delta\lambda$.

DGD-based approach. This method involves measuring the DGD as a function of wavelength for a given fiber channel, using standard telecom techniques. Using the derived formulas [(2) and (7)], we then calculate the infidelity as a function of the wavelength for the specified filtering bandwidth $\Delta\lambda$ ($\Delta\omega$).

In this section, we verify the consistency between these two methods and compare the obtained results with those observed in a real QKD setup.

In order to measure the DGD, we rely upon the frequency-domain measurement setup [24]. It consists of a tunable laser, a polarization controller, the fiber span itself, and a polarimeter connected in series; see the Supplemental Material (SM) [25] for differential-group-delay measurements. We performed polarization measurements on several 10-km deployed fiber links in Masdar City, Abu Dhabi. The DGD as a function of wavelength was extracted with the Mueller matrix method (MMM) [26]. A representative DGD trace for one of the links is shown in Fig. 4. The observed oscillatory behavior is characteristic and was reported previously (see [27], for example).

In Fig. 5, we compare the expected infidelity values obtained with these two methods for a fixed bandwidth of 5 nm. The infidelity values obtained from the numerical integration are smaller than those derived using the DGD-based method. We attribute this difference to the following considerations. An arbitrary polarization generally does not rotate around the PMD vector along the great circle. A random state can

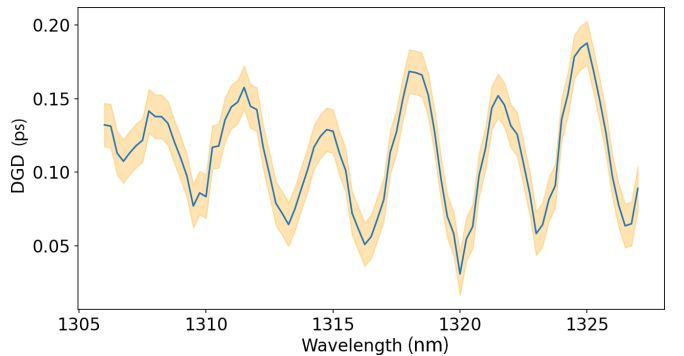


FIG. 4. The measured differential group delay vs wavelength obtained using the MMM [26] method. The error band represents the rms separation between two curves recorded with different input polarization states within a 30-min interval, providing an estimate of the method’s repeatability and DGD drift.

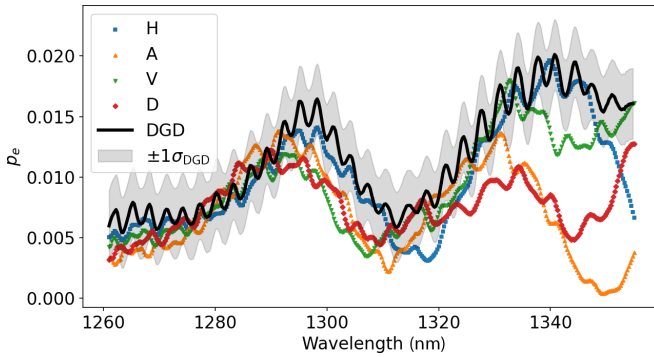


FIG. 5. Infidelity p_e for a 5-nm filtering bandwidth in a 10-km deployed fiber loop. Solid black line: DGD-based estimation using (7). Colored symbols: trajectory integration (4) for four different input polarization states, H , V , D , and A . The error bar corresponds to the temporal drift of the DGD measurement, which is the dominant source of DGD uncertainty in our setup.

rotate at any $\varphi < \pi/2$, as shown in Fig. 2(d), or can even converge to a point like for states $|1\rangle$ and $|3\rangle$ in Fig. 2(c). When we find infidelity from the DGD measurement (7), we assume the worst case of $\sin \varphi = 1$, corresponding to the rotation along the great circle in Fig. 2(b). Consequently, DGD-based infidelity represents an upper limit for the trajectory-integration method. Therefore, comparing the DGD calculation with the trajectory integration validates the proposed model.

In Fig. 6, we assess the correspondence between the two methods for estimating p_e while altering the filtering bandwidth $\Delta\lambda$. The relationship is quadratic and aligns closely with the proposed model.

Despite our focus on PMD effects, in real QKD experiments, it is impossible to isolate the PMD-induced infidelity from other contributions, such as background counts and basis misalignments. However, for short distances and relatively broad filtering bandwidths, we can reasonably expect PMD-induced errors to dominate over other factors. Moreover, the total error rate should at least exceed the PMD-related predictions for the system. To verify the consistency of our model with these assumptions, we conducted a series of experiments

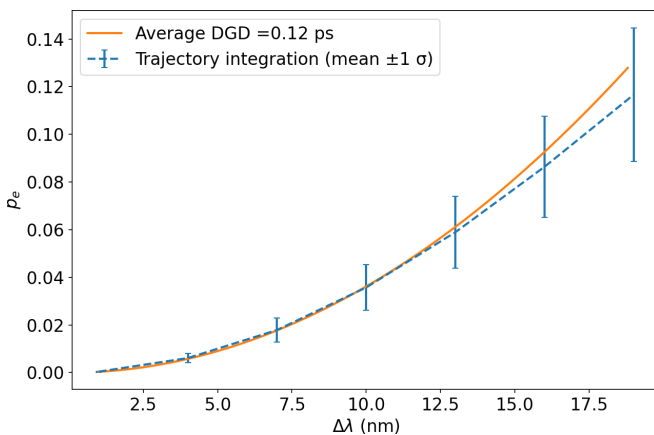


FIG. 6. Comparison of the infidelity calculation using the DGD-based approach (7) and the numerical trajectory integration (4) for a varying filtering bandwidth $\Delta\lambda$.

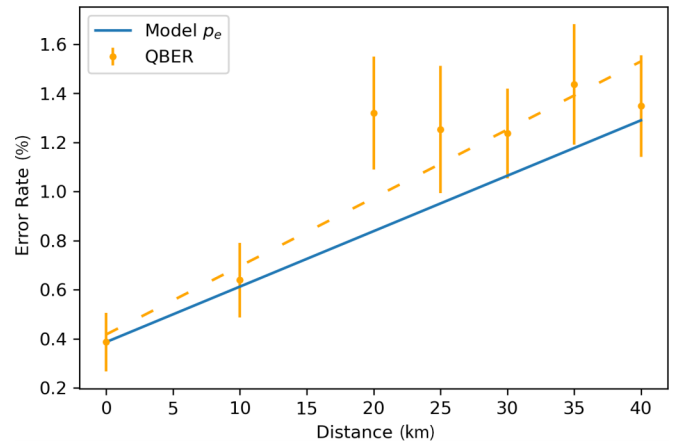


FIG. 7. Measured QBER and modeled infidelity p_e vs link distance. We used the coefficient $\text{PMD}_Q = 0.05 \text{ ps}/\sqrt{\text{km}}$ typical for our fibers (8). The dashed line represents the linear regression of the experimental QBER points and is provided as a visual guide. The modeled curve is shifted upward to match the QBER at zero distance, accounting for detector dark counts, timing jitter and synchronization errors, optical misalignment, imperfect source quality, and back-reflections or stray light.

using a self-made QKD setup prepared for real-world deployment. The setup is based on the same scheme used in [28], and a detailed description is given in the SM [25] (see the BBM92 QKD experiment description).

As a source of polarization-entangled photon pairs, our setup uses a periodically poled lithium niobate (PPLN) crystal within a linear displacement interferometer, applying a technique similar to that described in [29]. The PPLN crystal generates an SPDC spectrum centered at 1313 nm with an FWHM range of 30–100 nm. Factors such as crystal length, pump bandwidth, focusing conditions, and temperature influence the resulting spectrum. The photon pairs are separated into two channels using fiber Bragg filters with 2-nm subbands, while fiber spools were utilized to make up the distance.

For on-site detection, we used a passive-basis-choice optical scheme with IDCube single-photon detectors set to 20% detection efficiency. An automated polarization controller in one of the channels is employed to realign the polarization transformation, ensuring that it corresponds to measurements in two receivers. Polarization alignment is achieved through QBER minimization by using gradient descent optimization.

The trend of the measured QBER versus link distance (Fig. 7) is close to, but slightly higher than, the minimum possible value predicted by our PMD model. Up to 10 km, the measured QBER aligns with the PMD-induced QBER after a constant offset corresponding to the 0-km value is applied. As distance increases, the measured QBER grows faster than the PMD-induced contribution, with an average slope about 1.2 times higher (up to 40 km). This observation supports our estimation that, under the given conditions of our QKD system, the PMD-related QBER is dominant and validates the consistency of our model.

IV. DISCUSSION

Let us discuss possible ways of PMD mitigation in real-life entangled-based QKD scenarios. First, we look at the simplified model of the first-order PMD approximation. Later in this section, we also evaluate the contribution of higher-order PMD effects to QKD errors.

The overall impact of PMD-induced loss of fidelity on the QKD system strongly depends on the orientation of the four-state circle with respect to the PMD vector $\vec{\Omega}$. For the BBM92 protocol [i.e., Bennett-Brassard 1984 (BB84) bases arrangement], the maximal probability of error occurs when both bases lie on the great circle orthogonal to the PMD vector [Fig. 2(b)]. Each of the four states experiences the same maximally possible decoherence (6) at $\varphi = \pi/2$. Detection errors are thus equally observed in both bases.

As suggested above, in order to minimize the effect of PMD it is reasonable to align one of the measurement bases with the PMD axis [Fig. 2(c)]. In this case, the first-order PMD-related decoherence disappears for this particular one, while it remains at the maximal level for the other. Formally, this means that the average PMD-induced QBER is two times lower than in the worst case. However, from a practical point of view, it creates a strong asymmetry between the two bases, which is not always desirable, as it has to be properly accounted for during error-correction and privacy-amplification steps.

A more practical alternative orientation of the bases is when the PMD vector lies in the plane of the four-state circle but exactly in the middle of the arc between two adjacent measurement states [Fig. 2(d)]. Due to the factor of $\sin^2 \varphi$ in (6), the effective probability of errors is still 2 times smaller than in the worst case, but errors are evenly distributed between the two bases, which could lead to a more balanced operation and, potentially, better overall performance.

Moreover, if the protocol assumes unequal probabilities for the basis choice, as in [30], the resulting error distribution can be fine-tuned to achieve the optimal balance of the error rates with respect to the basis-choice asymmetry. In other words, the more probable basis should have a lower QBER by shifting the corresponding states closer to the PMD vector while keeping the latter within the four-state plane.

Interestingly, the average detection error probability for the six-state protocol [31] with equiprobable bases is completely invariant to the rotations of the bases with respect to the PMD vector. This pinpoints the greater symmetry of the six-state protocol with respect to the conventional BB84 protocol. However, the distribution of errors between the three bases is dependent on the orientation of the bases and can easily be symmetrized.

Let us now look at a few practical implementation examples to show the tools available for first-order PMD mitigation. For simplicity, let us assume that the source generates a singlet state $(|HV\rangle - |VH\rangle)/\sqrt{2}$, which can be obtained from the state (1) by applying the Pauli transformation σ_y to either of the qubits. The singlet state, being measured on any basis, always yields perfectly anticorrelated results. Therefore, to establish QKD, it is only required to match two transformations between the source and the two receivers. This can be achieved with a single polarization

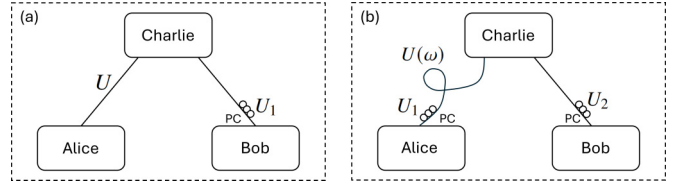


FIG. 8. Configurations with PMD mitigation: (a) local detection and (b) one local and one remote measurement. PC, polarization controller; U , unitary transformations of the polarization state.

controller, as shown in Fig. 8(a). It has to be set to perform the same transformation U , as in the other channel, so $U_1 = U$. However, if there is PMD in one of the channels, it is important to properly orient the measurement bases with respect to the PMD vector. As we show below, this can be done by introducing one more polarization controller.

This configuration is shown in Fig. 8(b): One of the photons is detected locally, while the other one passes through the long fiber line with a non-negligible PMD that we denote as a wavelength-dependent unitary polarization transformation $U(\omega)$. For simplicity, we will consider the case where one of the bases is aligned with the PMD vector. This can be done with the use of Alice's polarization controller placed between the channel and her measurement device. It should be tuned to perform the unitary transformation

$$U_1 = |H\rangle\langle p_1| + |V\rangle\langle p_2|, \quad (9)$$

where $\langle p_{1,2}|$ are the two PSPs.

Now, a second polarization controller is required to ensure identical transformations in both channels at some median wavelength ω_0 . It has to be tuned to perform $U_2 = U_1 U(\omega_0)$. In this configuration, the PMD does not affect correlations in the $|H\rangle$ - $|V\rangle$ basis and thus reduces its overall impact. By the choice of (9), it can be further tuned to become symmetric between the two bases or even to shift most of the errors toward the $|H\rangle$ - $|V\rangle$ basis, when it becomes farther away from the channel PSPs.

The situation may become even more interesting when the two long channels between Charlie, Alice, and Bob have their own PMDs. The results provided in the present work give a good idea of the tools available for PMD mitigation, which could easily be extended to this more complicated case.

Nonlocal PMD compensation was first theoretically proposed and studied in [32,33]. However, these previous results applied to our problem only say that the PMD can be fully compensated by adding a suitable PMD (not just polarization) compensator in one of the paths, as long as the SPDC source is pumped continuously. This poses little practical importance, as placing compensators in both paths, instead of just one, can compensate for any PMD-related distortions, regardless of the pumping scheme. However, no experimental tools exist for this task. In the present work, we only address *practical* tools of PMD mitigation. A study of this more complicated case with two extended channels utilizing compensation in a nonlocal fashion may result in more efficient practical PMD mitigation. However, that goes beyond the scope of the current paper and should be addressed in a separate research initiative.

Now, let us assess the significance of higher-order PMD effects in relation to their contribution to infidelity. First, our experimental results (Fig. 7) indicate that overall QKD errors align closely with those predicted by the first-order PMD model. Therefore, there is little scope for higher-order PMD effects to contribute significantly. This leads us to check this preliminary conclusion by numerical evaluation.

To evaluate it numerically, both the absolute value and the direction of the PMD vector $\vec{\Omega}$ must be examined because they vary with wavelength. Changes in the absolute value indicate variations in the speed at which the polarization rotates about $\vec{\Omega}$. Meanwhile, directional changes in $\vec{\Omega}$ lead to deviations of the four measurement states from the plane of the four-state circle. An explanation of the estimation methods is included in the SM [25] (see the section titled “Assessment importance of the high orders of PMD”). In the following, we summarize the key considerations and present the results.

For changes in the absolute value of $\vec{\Omega}$, we notice that the DGD shows oscillations with a period comparable to 1 nm (Fig. 4). This behavior is typical, as similar oscillations are observed in all our measurements and in [27], for instance. Taking it as a basis for a qualitative model, we conclude that this contribution to the measurement error probability is at least an order of magnitude smaller than the first-order contribution.

We assess the contribution of $\vec{\Omega}$ rotation to the infidelity by evaluating two specific types of polarization states (see the SM [25] for details). For the type-1 state, the infidelity is solely due to $\vec{\Omega}$ rotation. In the case of the type-2 state, the first-order mechanism is maximal. Then, we compare the infidelity for the type-1 state with that for the type-2 state. The result of this comparison shows that the contribution of $\vec{\Omega}$ rotation to the infidelity is an order of magnitude smaller than that given by the first-order mechanism. Interestingly, the contribution from $\vec{\Omega}$ rotation can even be beneficial for PMD mitigation, provided the DGD remains sufficiently small (see the end of the SM [25]).

In conclusion, while higher-order PMD effects contribute to infidelity, their impact is significantly smaller than that of the first-order effects.

V. CONCLUSION

For QKD optimization, many parameters are used, such as source brightness, channel losses, dark-count rate, detection efficiency, etc. They are involved in optimization models [34,35] to maximize key-generation rates after the last post-processing stage, privacy amplification. We expanded these models to take into account PMD-related channel parameters and optimize the filtering bandwidth of broadband entangled photon sources.

Our model, validated through experimental measurements, shows a quadratic relationship between infidelity and filtering bandwidth, as well as a linear relationship between infidelity and QKD distance. A simple way to halve the effects of PMD is to align the measurement bases with respect to the PMD vector in such a way that the PMD vector lies in the four-state circle plane. This can be achieved using an additional polarization controller in the scheme, minimizing QBER. At the same time, it is possible to achieve a balanced error distribution in the measurement bases.

More detailed experiments, as well as further PMD mitigation exploiting nonlocal PMD compensation, are left for future work. By understanding and mitigating the effects of PMD, we can improve the security and reliability of QKD systems. We believe that our contributions can potentially benefit QKD, quantum communications, and fiber-optic data transfer.

ACKNOWLEDGMENTS

This project is funded by Abu Dhabi’s Advanced Technology Research Council. The authors thank K. Sloyan, J. Singh, A. Trushechkin, R. S. Piera, and V. Revici for support for various aspects of the QKD system and J. Villegas for support in the early stages of our PMD measurements.

The authors declare no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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