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High-Dimensional Quantum Cloning

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***Abstract:** Tries at cloning a quantum tool result in the arrival of imperfections in the nation of the copies. this is a outcome of the no-cloning theorem, that is a vital law of quantum physics and the spine of protection for quantum communications. in spite of the reality that ideal copies are prohibited, a quantum country may be copied with maximal accuracy through severa most top notch cloning schemes. maximum beneficial quantum cloning, which lies at the border of the bodily restrict imposed by way of the no-signaling theorem and the Heisenberg uncertainty principle, has been experimentally found out for low-dimensional photonic states. however, an growth in the dimension-ality of quantum structures is notably beneficial to quantum computation and communication protocols. despite the reality that, no experimental demonstration of most beneficial cloning machines has hitherto been shown for excessive-dimensional quantum systems. We carry out most proper cloning of excessive-dimensional photonic states thru the symmetrization approach. We display the universality of our technique thru carrying out cloning of numerous arbi-trary enter states and really signify our cloning tool with the useful resource of appearing quantum nation tomography on cloned photons. similarly, a cloning assault on a Bennett and Brassard (BB84) quantum key distribution protocol is ex-perimentally showed to expose the robustness of excessive-dimensional states in quantum cryptography.*
***Keywords:** QKDP, BB84, quantum bit, OAM*

I. INTRODUCTION

Quantum cryptography is more precisely Quantum key distribution protocol (QKDP) is a new technology which gets a high level of attention today worldwide. The possibility to exchange information in a provable secure way is a culmination in communication history. The main problem in quantum key distribution is the range of circumspection between the communication associate Alice and Bob. In the BB84quantum key distribution protocol in two associate authorize a secret key about which the Eavesdroppers cannot obtain a compelling amount of information. Alice sends a key bit to Bob by preparing a qubit (quantum bit) in one of two conjugate bases and Bob measures the qubit in one of the two bases, Eva, who does not know the support chosen by Alice or by Bob, cannot information about the key without generating a detectable disturbance. The BB84quantum key distribution protocol is implemented n two phases which are as follows

A. The First Phase(over the Quantum Channel)

1) Alice first forms the raw key string which comprises of a random order.
2) After this, using the random basis sequence using, she transmits the polarized photon sequence to Bob.
3) Bob will measure the incoming photon sequence using his basis sequence.
4) As Bob doesn't know the basis sequence of Alice, thus it is not deterministic basis sequence.

B. The Second Phase(Over a Public Channel)

1) Bob and Alice exchange the basis sequence used by each other.
2) After the basis exchange, the common matched bases points are kept intact while the different bases are discarded.
3) At this stage, Alice and Bob have the common raw bit sequence after all the acceptance and rejection of bases but this cannot be treated as the final secret key has Eva can intercept this photon sequence.
4) To achieve the final secret key, Error estimation(estimating the amount of error occurred during the whole transmission procedure), Error correction(perform the necessary error correction measures), and privacy amplification (detect the presence of Eva and regenerate the key using the same procedure until the surety of the secret key is established) are performed as final step.

C. Description of Cloning attack on quantum cryptography

Quantum cloning is one of method to meapositive information from input state. However several theoretical studies have been established, namely optimal universal quantum cloning (Brub et al., 1998). Pauli cloning machine of a quantum bit (Cerf, 2000) quantum copying beyond the no-cloning theorem (Buzek and Hillery, 1996) in a network (Buzek et al., 1997). The cloning of sequences of qubits encoded within the same basis has been studied with the six state BB84 protocols**.**

The safety of BB84 protocol (Bennett and Brassard, 1984) rests on the impossibility of the perfect cloning. If a eavesdropper has a perfect copying machine, it would be enough for him to copy the qubits that it intercepts, then to ship a copy to the receiver and to keep the other until the transmitter and the receiver announce their bases of meaursement. Immoderate-dimensional records is a promising location of quantum information technology that has matured during the last years. it is far saidentity that, with the aidentity of the usage of manner of the united statesage of not handiest qubits but moreover qudits, that is, d-dimensional quantum states, it's far possible to encode greater statistics on a single company, growth noise resistance in quantum cryptography protocols (1), and loookay into crucial homakes use of of nature (2). Photonic structures have been proven to be promising candidates in quantum computation and cryptography for lots evidence-of-principle demon-strations further to for “flying” quantum corporations to distribute excessive-dimensionally encoded states. Orbital angular momentum (oam) of moderate, which offers an unbounded united states of america space, has extended been recog-nized as a a laughctionality excessive-dimensional degree of freedom for wearing out experiments on the foundations of quantum mechanics (three, four), quan-tum computation (5), and cryptography (6). The primary feature of photons sporting oam is their twisted wavefront, characterised through An expðiʻφþ phase term, in which ʻ is an integer and φ is the azimuthal coordinate (7). inside the context of quantum facts, oam states of photons have the advantage of representing quantum states be-longing to an infinitely big, however discrete, hilbert area (eight). Finite subspaces of period d may be considered as laboratory realizations of photonic qudits. right here, we adopt the oam degree of freedom of unmarried photons to gain excessive-dimensional quantum cloning and perform quantum hacking on a immoderate-dimensional quantum communication channel. Notwithstanding the fact that excellent cloning of unknown quantum states is forbidden (nine), it is far exciting to invite how similar to the preliminary quantum us of a the notable feasible quantum clone may be. The solution is given In phrases of the cloning constancy f, that is described because the overlap between the initial country to be cloned and that of the cloned copies. This discern of advantage is a degree of the accuracy of a cloned duplicate received from a particular cloner. Schemes that acquire the quality viable constancy are called plodgeacle-rated quantum cloning and play an vital role in quantum information

II. RELATED WORK

A. Cloning Attack In Quantum Cryptography

As a totally last check of the functionality to clone excessive-dimensional quantum states, we put into impact a cloning attack right into a excessive-dimensional quantum key distribution (QKD) scheme. In a QKD protocol, a sender (Alice) and receiver (Bob) use quantum states to distribute a random, mystery key shared between both occasions. The shared key is then used to commu-nicate an encrypted message through a classical channel, the use of the perfectly comfy one-time pad protocol. the safety of QKD derives from thefactthatthepresenceofaneavesdropper (Eve) will bring about the advent of errors inside the shared key, that could originate, as an instance, from the nonperfect but most useful cloning executed via the eaves-dropper (24). notice that the dimensionality of the quantum states used to distribute the essential thing right now impacts the cloning constancy and as a result the quantity of mistakes introduced with the aid of a probable cloning attack.

We first carry out a excessive-dimensional QKD using the seminal BB84 protocol (22), extended using OAM states of dimension

7. An eavesdropper with get right of entry to to a excessive-dimensional UQCM then plays man or woman assaults at the QKD channel. In our check, the number one MUB is given via the logical OAM basis fj‘〉; ‘ ¼ -three; - 2; - 1; 0; 1; 2; 3g, and the second MUB is given with the useful resource of the Fourier perspective foundation {|fi〉; i = 1, 2, three, four, 5, 6, 7}. Projective measurements are shown with and without the cloning attack in Fig. four (A and B), respectively. The lower fidelity because of a cloning attack is without difficulty seen. A visually compelling instance of the impact of an eavesdropper on Alice and Bob’s shared key may be given through di- rectly using the installed uncooked

sifted key, with out appearing further mistakes correction and privacy amplification, as a one-time pad to percent an encrypted message, for instance, an picture of their favourite optical phenomenon. We experimentally simulate this kind of state of affairs by way of way of performing the immoderate-dimensional BB84 protocol with and with out Eve's attack the use of our UQCM. In a real-global QKD, experimental er- rors will constantly be added in the uncooked key, leading to a slightly de- teriorated picture after Bob's decryption . but, if Eve performs her cloning attack while Alice and Bob are in search of to set up their key, the errors increase drastically, this is then directly seen in Bob's decrypted photograph (see Fig. 4B). The quantum bit blunders rate (QBER) is given by means of manner of 0.sixteen and zero.57, with out and with the cloning assault, respectively. inside the absence of an eavesdropper, the QBER is well below the error sure for protection in length 7, this is, Dcoh = 23.72% (1). because of this, mistakes correction and privateness amplification may be done so as for Alice and Bob to obtain a very cozy and errors- much less shared key. however, inside the presence of the eavesdropper, the QBER is well above the certain in measurement 7, right away revealing the presence of Eve. furthermore, the mutual information amongst Alice and Bob can be calculated from AB ¼ log2ðdÞþ ð1 - eB Þ log2ð1 - eB Þþ eB log2(eB =ðd - 1Þ) wherein eN is Bob's blunders fee (25). Experimental values of one.73 and zero.36 bits in line with photon had been obtained for Alice and Bob's mutual facts with out and with the cloning assault, respectively. similarly, we in step with- common quantum hacking to a -dimensional QKD protocol (BB84). In this situation, the QBER is given by means of 0.19 and 0.007, with and without the cloning attack, that is nicely above and beneath the safety certain in dimension 2, that is, Dcoh(2) = eleven.00%, respectively. for this reason, it is smooth that immoderate-dimensional quantum cryptography outcomes in higher sign disturbance in the presence of an maximum useful cloning attack, resulting in a bigger tolerance to noise inside the quantum channel

III. METHODOLOGY

The experimental setup can be divided into three elements: a unmarried-photon source, a hom interferometer, and a cloning characterization appara- tus (see fig. S1). Unmarried-photon pairs had been generated with the aidentity of the manner of spontaneous parametric down-conversion at a nonlinear type i b-barium borate crystal illuminated through a quasi-continuous wave ultraviopermit laser working at a wavelength of 355 nm. The single photons have been spatially filtered to the essential gathe usan mode by way of coupling the generated pairs to unmarried-mode optical fibers, with a measured twist of fate charge of 30 khz, interior a twist of fate time window of 5 ns. The associate photons have been each made to mild up an slm, to generate the favored photonic states, and inside the long run sent at a 50:50 nonpolarizing beam spmuddle, one at each input port. The direction taken through the photons, generated on the non-linear crystal to get to the beam spclutter, have to be equidistant for each photons of a given pair to take a loook at the two-photon interference impact. This could be done with a precision of tens of micrometers the use of a programmable translational diploma. polarizers and interference filters had been inserted in the cousaa. of each photon. The photons have been then made in- distinguishable in arrival time, polarization, and frequency. However, the spatial modes of the photons were stored as a degree of freedom representing photonic quantum states for the uqcm. Following the hom interference beam spmuddle, the bunched photons have been despatched to a 2nd beam splitter, retaining apart them for further accident detection. Last, the separated output cloned photons were detected and character- ized with slms followed via single-mode optical fibers

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Optimal quantum cloning with OAM states of single photons We use the symmetrization method to realize a universal optimal quantum cloning machine for high-dimensional OAM states (17, 18). In this method, the quantum state that is to be cloned, namely, |y⟩, is sent to one of the input ports of a nonpolarizing beam splitter. In the other input port, a completely mixed state of the appropriate di- mension, given by ^rmix ¼ Id =d, is sent, where Id is the d-dimensional identity matrix. The symmetrization method relies on the well-known two-photon interference effect at a 50:50 beam splitter first proposed by Hong et al. (19). When two indistinguishable single photons enter a beam splitter, one into each input port, the photons will "bunch" because of their bosonic nature and exit the beam splitter togethe through the same output port. This principle is the essence of the symmetrization method for optimal quantum cloning. When both input photons are interfering at the beam splitter, two "cloned" photons will jointly exit one of the output ports. We note that this cloning scheme does not require knowledge of the input state and applies to any ar- bitrary state. This property is a result of the "universality" of the clon- ing machine and shows the versatility of our scheme.

Each state of the output cloned photon is represented by a reduced density matrix ob- tained by tracing over the other photon. Because both cloned photons are characterized by an identical cloned state, the cloner is thus said to be "symmetric." Hence, the symmetrization method is considered to be a symmetric optimal universal quantum cloning machine (UQCM). In our experiment, we implement a high-dimensional ver- sion of this UQCM with OAM states of single photons (see Fig. 1). We generate and measure the OAM states by manipulating the phase front of the photons using a liquid crystal phase-only spatial light modulator (SLM) (see the Supplementary Materials for a more detailed experimental discussion).

Cloning fidelity To characterize the quality of our UQCM, we use two different approaches to evaluate the yielding cloning fidelities: measuring the probability of successful cloning and full-state tomography of the cloned photons. In this first series of measurements, we evalu- ate the cloning fidelity, F y , of a given arbitrary input state, |y⟩, from the probability of finding both output cloned photons in the state |y⟩, that is, Pðjy⟩; jyiÞ. This probability can be obtained experimentally by means of coincidence measurements: F y ¼
Pðjy⟩; jyiÞ ¼ (Nðjy⟩; jyiÞ þ ∑i≠y Nðjy⟩; jii)=Ntot , where N(|i⟩, |j⟩) represents the number of coincidence measurements between the states |i⟩ and |j⟩, Ntot is the total number of coincidence measure- ments (that is, Ntot = N(|y⟩, |y⟩) + 2∑i≠yN(|y⟩, |i⟩)), and |i⟩ and |j⟩ represent elements of the basis containing |y⟩. The factor of 2 that appears in the definition of Ntot is a result of the symmetric nature of our cloning machine, where N(|i⟩, |j⟩) = N(|j⟩, |i⟩). Further, one can obtain from normalization, Pðji⟩; jyiÞ ¼ Nðji⟩; jy⟩Þ=Ntot , for i ≠ y. Here, we note that the optimal cloning fidelity depends on the HOM interference visibility V through the relation

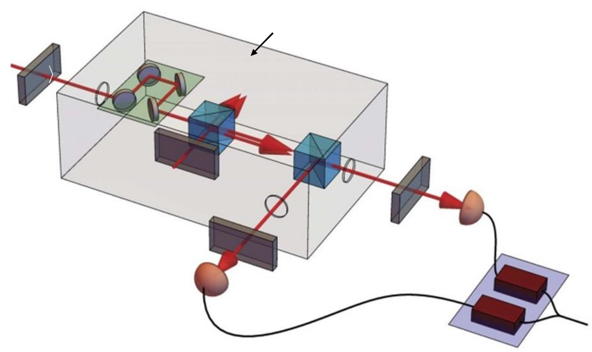

Fig. 1. Simplified sketch of the experimental design. The input quantum state |y⟩ is imprinted on a single photon using an SLM-A. The single photon is subse- quently sent to the cloning machine for optimal cloning. The cloning machine consists of a delay line (DL), to adjust the arrival time of the input photon, a second photon that is in a completely mixed state when exiting SLM-B, and a first beam splitter (BS1). The two photons are made to arrive at the beam splitter simultaneously using the DL. The two photons exiting one of the output ports of the first beam splitter together are separated at a second beam splitter (BS2) and are sent out of the cloning machine. The cloned photons are then detected and characterized using detectors (D1 and D2) and SLMs (SLM-C and SLM-D), respectively. (A to C) Examples of Hong-Ou-Mandel (HOM) coalescence curves for input photons of ‘ ¼ -1; 0; 1; respectively (top to bottom). The curve is obtained by recording the coincidences between the output ports of BS2 for various delays of one of the input photons. Examples of enhancement peaks of R‘¼-1 ¼ 1:97 ± 0:08, R‘¼0 ¼ 2:02 ± 0:08, and R‘¼1 ¼ 1:99 ± 0:09 are obtained experimentally, and agree with the theoretical value of Rth = 2, corresponding to a visibility of V ¼ 1.

V. CONCLUSION

In conclusion, we showed the feasibility of high-dimensional optimal quantum cloning of OAM states of single photons. This scheme was further used to perform a cloning attack to a secure quantum channel, revealing the robustness of high-dimensional quantum cryptography upon quantum hacking. Moreover, studying the effect of dimension- ality and universality on optimal quantum cloning reveals its advan- tage over optimal state estimation in quantum information schemes, where unknown quantum states must be distributed.

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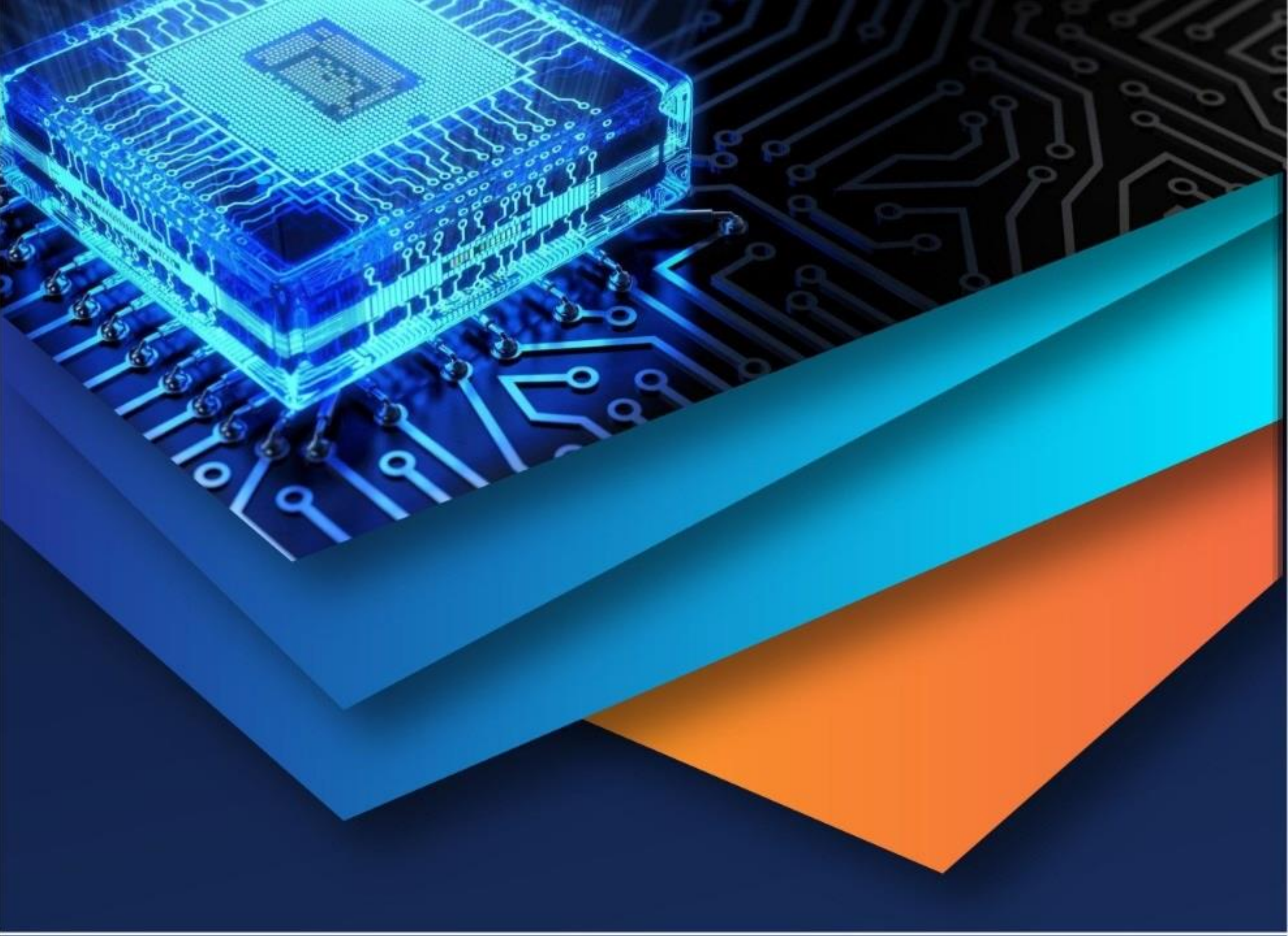

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