Quantum information technology with Sagnac interferometer: interaction-free measurement, quantum key distribution and quantum secret sharing

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The interferometry of single-photon pulses has been used to implement quantum technology systems, like quantum key distribution, interaction-free measurement and some other quantum communication protocols. In most of these implementations, Mach–Zehnder, Michelson and Fabry–Pérot interferometers are the most used. In this work we present optical setups for interaction-free measurement, quantum key distribution, quantum secret sharing and secure classical prisoners' dilemma game using the Sagnac interferometer. The proposed setups are described and as well the quantum protocols using them are explained.

Keywords: Sagnac interferometer; quantum protocols; interaction-free measurement

1. Introduction

Quantum information technology is the new engineering area responsible for the experimental realization of quantum communication protocols and quantum computers. However, in despite of the potentialities of quantum information to provide new ways of communication and computation, to work with quantum data is still a hard task. For quantum gate implementations, several different technologies have been tested, with optical and photonic devices [1–5], quantum dots [6], superconducting devices [7,8], semiconductors [9,10] and nuclear magnetic resonance [11–13] being the most important ones. For example, an all-optical CNOT gate has been implemented in [14]. On the other hand, for quantum communication purposes, optical and photonic devices form, up to now, the main technology used. This happens because, among other reasons, light polarization and time-bin [15] are qubits that are relatively easy to create, process and detect; photons can be sent far way propagating in an optical fiber, although for long distance quantum communication, a polarization encoded qubit requires an error

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correction procedure because of random variations of the birefringence of single-mode fibers [16,17]; and interferometry of single-photons is a powerful technique to observe quantum phenomena. In fact, most experimentally realized quantum key distribution (QKD) setups were implemented using light polarization and/or single-photon interferometry (with weak coherent states and true single-photons). Furthermore, the interferometry of single-photons can also be used for interaction-free measurement, whose goal is to identify the presence of an object without any interaction with the same. Most of the realizations of quantum technology using interferometry of single-photons have used Mach–Zehnder, Michelson or Fabry–Pérot interferometers. On the other hand, the Sagnac interferometer is also an important tool for quantum technology purposes and it has been used, for example, in the optical implementation of Grover’s algorithm [18] and quantum metrology [19]. In this work we present optical setups for interaction-free measurement, QKD, quantum secret sharing and secure classical prisoners’ dilemma game using the Sagnac interferometer. The proposed setups and the quantum protocols for their use are explained.

This work is outlined as follows: in Section 2, interaction free-measurement with Sagnac interferometer is discussed. In Section 3, QKD using a Sagnac interferometer is presented. In Section 4, the setup for quantum secret sharing between five persons using Sagnac is shown. In Section 5, an optical setup based on a polarization interferometer for implementation of secure classical prisoners’ dilemma game is presented. Finally, the conclusions are presented in Section 6.

2. Interaction-free measurement using Sagnac interferometer

The fascinating experiment of interaction-free measurement consists of identifying the presence of an object in a determined place without interacting in any way with the object. The key property that allows such a task to be realized is the wave–particle characteristic of single particles like photons. This wave–particle behavior is readily observed in single-photon interferometry, in fact, the first interaction-free experiment was proposed in [20] using single-photons in a Mach–Zehnder (MZ) interferometer, as shown in Figure 1.

In Figure 1 C1 and C2 are balanced optical couplers (an optical coupler is a fiber-based device equivalent to a bulk beam splitter) while SPDs are single-photon detectors. For the interaction-free experiment $\phi_A = \phi_B$, that is, when the object is absent the photon behaves like a wave and it emerges always at the ’0’ output, as shown in part (a) of Figure 1.

![Figure 1](image-url)  
Figure 1. Interaction free measurement using single-photon pulses and Mach–Zehnder interferometer having $\phi_A = \phi_B$. (a) Object not inserted implies wave behavior. (b) Object inserted implies particle behavior.
On the other hand, when the absorber object is present in one of the interferometer arms, the photon behaves like a particle and it will be detected, with probability 25% at output ‘1’, as shown in part (b) of Figure 1. Hence, every time detection occurs at output ‘1’, in an ideal noiseless system, one can be sure the object is present. The interaction-free experiment of Figure 1 has low efficiency since the probability of getting a correct and conclusive result when the object is present is only 25%. A higher performance interaction-free experiment using single-photon polarization was proposed in [21,22], and it can be seen in Figure 2.

In Figure 2, R(±Δφ/2) are polarization rotators of ±Δφ/2; M₁ is a single-direction mirror, that is, light is highly transmitted from left to right and highly reflected from right to left; M₂ and M₃ are common mirrors; FM is a Faraday mirror that rotates the input light polarization of π/2; P is a Pockels cell that rotates light polarization of π/2 when it is activated. The polarizing beam splitter guides the input light as shown in Figure 3.

The goal of the experiment in Figure 2 is to determine, without interaction, which one is being used, M₂ or FM. When M₂ is being used the photon behaves like a wave and its polarization is rotated from horizontal to almost vertical due to successive actions of the polarization rotator R(Δφ/2). After N runs, the photon polarization is |NΔφ⟩ that can be made very close to |π/2⟩ (vertical) controlling N and choosing Δφ properly. At this

![Figure 2. Interaction-free experiment using single-photon polarization.](image)

![Figure 3. Guiding of input polarization states through 2 × 2 PBS.](image)
moment \( (N\Delta\phi \sim \pi/2) \) both Pockels cells are activated. The photon arrives in PBS\(_1\) coming from M\(_2/M_3\) and it is guided to PBS\(_2\) having polarization \( |N\Delta\phi + \pi/2\) (almost horizontal) and it is detected in D\(_H\) with probability very close to 1. On the other hand, if FM is used the photon behaves like a particle. In this case, for each run, if the photon is not detected in D\(_H\), one can be sure its polarization is \(|0\rangle\), hence, the polarization rotation due to successive actions of R(\(\Delta\phi/2\)) will not be accumulative and, after \(N\) runs without detection in D\(_H\), the polarization of the photon coming from M\(_2/M_3\) will be horizontal. Activating the Pockels cells, the polarization will become vertical and it will be guided to PBS\(_2\) and detected in D\(_V\). Hence, in order to have a good performance for interaction-free measurement, the following conditions must be satisfied:

\[
N\Delta\phi \sim \pi/2 \quad \text{and} \quad \cos^2(\Delta\phi)^N \sim 1,
\]

where this last condition is the probability of none detection in D\(_H\) after \(N\) runs when FM is being used. Choosing \(\Delta\phi = \pi/(2N)\), \(\cos^2(\Delta\phi)^N\) tends to \(1 - \pi^2/(4N) + O(N^{-2})\) for \(N\) large. A third implementation of interaction-free measurement using a Fabry–Pérot (FP) interferometer was proposed in [23]. In this one, as shown in Figure 4, the object is inserted or not inside the interferometer. If the object is absent, the FP interferometer has high transmissivity and the photons are detected in D\(_1\). On the other hand, if the object is present, the FP transmissivity decreases and some photons will be detected in D\(_0\).

Up to now, one can see that interaction-free measurement experiments have been proposed using MZ, Michelson and FP interferometers. Now we show how to construct an interaction-free measurement experiment using the Sagnac interferometer [24]. The proposed setup can be seen in Figure 5.

![Figure 4](image1.png)

**Figure 4.** Interaction-free measurement using Fabry–Pérot interferometer. M\(_1\), high reflectivity mirror.

![Figure 5](image2.png)

**Figure 5.** Interaction-free measurement using Sagnac interferometer. R(\(\theta\)) is a polarization rotator and C is a balanced optical coupler.
The goal of the setup in Figure 5 is to determine, without any interaction, which one is connected to circulator $C_3$, i.e. mirror $M_2$ or detector $D_2$. For the correct functioning, the paths $H$–$H$ and $V$–$V$ must have the same length. The light emitted by laser diode LD is assumed to be horizontally polarized. Let us initially suppose that $M_2$ is connected. In this case, for any value of $\theta$, the photon will behave like a wave and it will always be detected in $D_0$. On the other hand, if $D_2$ is connected, depending on the $\theta$ value the photon will behave like a wave ($\theta = 0$), a particle ($\theta = \pi/2$) or both at the same time ($0 < \theta < \pi/2$). The probabilities of detection in $D_0$ ($P_0$), $D_1$ ($P_1$) and $D_2$ ($P_2$) are, respectively, given by

$$P_0 = \cos^2(\theta) + \frac{\sin^2(\theta)}{4},$$  \hspace{1cm} (1)

$$P_1 = \frac{\sin^2(\theta)}{4},$$  \hspace{1cm} (2)

$$P_2 = \frac{\sin^2(\theta)}{2}.$$

Therefore, the probability of identifying that the device connected in $C_3$ is the detector $D_2$ without losing the photon, that is, having detection in $D_1$, is given by (2), whose maximal value is 25% for $\theta = \pi/2$. Thus, the setup in Figure 5 is, in terms of efficiency, equivalent to the setup shown in Figure 1. However, using the setup presented in Figure 6, one can determine the presence of $D_2$, without interaction, with probability close to 1 for each photon used.

The functioning of the setup in Figure 6 is similar to the functioning of the setup presented in Figure 2. Firstly, the photon emitted by the laser source LD is horizontally polarized and the electro-optical switch is connecting circulator $C_1$ to mirror $M_4$. If $M_2$ is connected, the photon comes into and leaves the Sagnac interferometer several times and, for each time, its polarization is rotated of $\Delta \theta$ by polarization rotator $R(\Delta \theta/2)$. After $N$ runs, the photon polarization will be vertical or close, depending on the values of $N$ and $\Delta \theta$. At this moment ($N\Delta \phi \sim \pi/2$) the electro-optical switch is switched connecting circulator $C_1$ to PBS$_3$. Thus, the photon is guided by $C_1$ forward to PBS$_3$ and it will be

![Figure 6](image_url)
detected in \( D_{0V} \) with high probability. On the other hand, if \( D_2 \) is connected, then photon polarization will not suffer accumulative rotation and, after \( N \) runs, the electro-optical switch is switched and the photon is guided by \( C_1 \) forward to PBS\(_3\) and detected in \( D_{0H} \) with probability \( \cos^2(\Delta \theta) \). As it happens in the experiment in Figure 2, the probability of the photon surviving after \( N \) runs with \( D_2 \) connected is \( [\cos^2(\Delta \theta)]^N \). There is an interesting difference in the performances of setups shown in Figures 2 and 6. In Figure 2, with FM connected, the probability of the photon to interact with FM per run is \( \sin^2(\Delta \phi) \), while in Figure 6, with \( D_2 \) connected, the probability of the photon to interact with \( D_2 \) is lower than \( \sin^2(\Delta \theta) \). This happens because the photon can propagate clockwise or counter-clockwise directions. In this last case, for vertical polarization, the photon will be detected in \( D_1 \) with probability 0.5.

Lastly, although we have discussed the use of the wave–particle behavior only for interaction free-measurement of absorbers, it can also be used, for example, in the measurement of a photonic qubit without destroying it [25].

3. Quantum key distribution using Sagnac interferometer

Quantum key distribution (QKD) [15,26,27] is the first quantum technology commercially available. QKD experiments have been realized using MZ, Michelson and Sagnac interferometers. The first proposal of QKD using Sagnac, named circular type QKD, was proposed in [28]. The optical setup is shown in Figure 7.

The optical setup of Figure 7 works as follows: initially Bob sends a bright optical pulse. This pulse is split in two by the balanced optical coupler. One half going to Alice is clockwise (\( P_{\text{Clik}} \)) and the other half going to Alice is counter-clockwise (\( P_{\text{CClik}} \)). The pulse \( P_{\text{Clik}} \) arrives first at Alice, since the pulse \( P_{\text{CClik}} \) passes first by the delay line. Once at Alice, the pulse \( P_{\text{Clik}} \) suffers attenuation in \( A \), it has its polarization corrected by \( P_{\text{CA}} \) and it passes by \( P_{\text{MA}} \) without being modulated. Finally, it returns to Bob. Once in Bob, \( P_{\text{Clik}} \) passes by the delay line, it has its polarization corrected by \( P_{\text{CB}} \), it is phase modulated by \( P_{\text{MB}} \) and, at last, arrives at optical coupler \( C \). The pulse \( P_{\text{CClik}} \) passes by \( P_{\text{MB}} \) without being modulated, after it passes by \( P_{\text{CB}} \), the delay line and it then follows on to Alice. Once at Alice, \( P_{\text{CClik}} \) is phase modulated by \( P_{\text{MA}} \), it has its polarization corrected by \( P_{\text{CA}} \), it is attenuated by \( A \) and it goes straight forward to optical coupler \( C \) at Bob. Both pulses arrive at \( C \) at the same time and interference will take place. Depending on the phase

![Figure 7. Circular type QKD. C, balanced optical coupler; PM, phase modulator; A, attenuator; PC, polarization controller.](image-url)
difference applied by Alice in $P_{CCl k}$ and by Bob in $P_{Cl k}$, the photon will be guided to SPD $D_0$ or $D_1$. Since both pulses take the same path, fluctuations of phase shifts are automatically compensated. The attenuation value of $A$ is such that pulse $P_{CCl k}$ leaves Alice having mean photon number close to 0.1. Another proposal of QKD using the Sagnac interferometer was presented in [29]. In this one, an acoustic-optical phase modulator was used in Alice, making polarization control easier, and as well some care was taken in order to avoid a Trojan horse attack.

Different to the setups proposed in [28,29], the setup proposed in this work is of the one-way type and, as happens with QKD using a MZ interferometer, it is (ideally) naturally protected against Trojan horse attack. The setup of the proposed Sagnac-based QKD can be seen in Figure 8. As can be observed, it uses light polarization and the Sagnac interferometer belongs only to Bob.

The QKD protocol using the setup of Figure 8 works as follows: Alice sends single-photon pulses to Bob. For each pulse sent Alice chooses randomly its polarization according to the codification: Basis 1 of Alice – $(0(0), \pi/2(1))$; Basis 2 of Alice – $(\pi/4(0), 3\pi/4(1))$ (in $X$ ($Y$, $X$ is the polarization and $Y$ is the bit value it represents). For each photon that arrives at Bob, he applies a polarization rotation, randomly chosen, according to the codification: Basis 1 of Bob – $(0(0), -\pi/2(1))$, Basis 2 of Bob – $(-\pi/4(0), -3\pi/4(1))$. After transmission of all photons, Alice and Bob say publicly which bases they have used and, in the cases where Alice and Bob chose the same bases, Bob says to Alice in which detector he had detection $D_H$ or $D_{V(1or2)}$. Having this information and knowing the polarization of her photon, Alice can discover which polarization, and hence, the bit Bob chose. In fact, when Alice and Bob choose the same bases ($\theta_A + \theta_B = 0$ or $\pm\pi/2$) the photon impinging on the Sagnac has horizontal or vertical polarization. In the first case the photon behaves like a wave suffering interference in $C$ and being detected in $D_H$. In the second case, the photon behaves like a particle and, if it is clockwise it will be detected in $D_{V1}$. If the photon is counter-clockwise, it will be detected in $D_{V2}$. When Alice and Bob choose wrong bases ($\theta_A + \theta_B = \pm\pi/4$) the photon behaves like a wave and a particle at the same time and it can be detected everywhere $D_H$, $D_{V1}$ or $D_{V2}$. As can be observed, this QKD protocol is closely related to the wave–particle behavior. This does not happen with the BB84 protocol in the MZ interferometer, for example.

![Figure 8. Optical scheme for polarimetric QKD using a Sagnac interferometer.](image-url)
4. Secret sharing using Sagnac interferometer

Let us suppose the following problem: there exist a secret, a bit sequence $K$ of length $|K|$. This secret is shared among five persons in such way that none of them knows $K$. Each person has their own secret: Fred ($K_F$), Alice ($K_A$), Bob ($K_B$), Charlie ($K_C$) and David ($K_D$). The bits sequences obey the conditions $K \neq K_F \neq K_A \neq K_B \neq K_C \neq K_D$ and $|K| = |K_F| = |K_A| = |K_B| = |K_C| = |K_D|$. Fred is the one who will use the secret $K$, but he will need cooperation of his locally distant partners Alice, Bob, Charlie and David in order to obtain the correct secret $K$. This means that if one of the partners does not use its correct secret, Fred will, with high probability, not obtain the correct $K$. The optical setup of Figure 9 can be used for such a task.

The probabilities of detection in $D_0$ ($P_0$) and $D_1$ ($P_1$) are given by

$$P_0 = \cos^2(\theta) \cos^2\left(\frac{\phi_a - \phi_b}{2}\right) + \sin^2(\theta) \cos^2\left(\frac{\phi_c - \phi_d}{2}\right),$$  \hspace{1cm} (4)

$$P_1 = \cos^2(\theta) \sin^2\left(\frac{\phi_a - \phi_b}{2}\right) + \sin^2(\theta) \sin^2\left(\frac{\phi_c - \phi_d}{2}\right).$$  \hspace{1cm} (5)

When detection occurs in $D_0$ bit 0 is obtained while detection in $D_1$ implies bit 1. Observing (4) and (5), one can see that Fred chooses who will define the bit value, Alice ($a$) and Bob ($b$), if Fred chooses $\theta = 0$ or Charles ($c$) and David ($d$), if Fred chooses $\theta = \pi/2$. The possible values of the angles are $\theta \in \{0, \pi/2\}$, $\phi_{abcd} \in \{0, d\phi, 2d\phi, 3d\phi, \ldots, N\,d\phi + \pi\}$. The secrets that Alice, Bob, Charlie and David have are the sequences of phase shift that they have to apply. In order to have deterministic detections by Fred it is necessary to have $\phi_a - \phi_b$ and $\phi_c - \phi_d$ equal to 0 or $\pi$ rad. Thus, the secrets that Alice and Bob have must be in such a way that, if Alice has to apply the phase shift $k\,d\phi$, Bob’s secret must indicate he has to use the phase shift $k\,d\phi$ or $k\,d\phi + \pi$, according to the bit value of the secret $K$, if 0 or 1, respectively. The same happens with Charlie and David. Hence, if, for example, David uses a different bit sequence, other than $K_D$, for those bits where Fred chose $\theta = \pi/2$, it may happen $\phi_c - \phi_d \neq 0$ and $\pi$. In this case, the photon will be detected in $D_0$ with probability $\cos^2[(\phi_c - \phi_d)/2]$ and it will be detected in $D_1$ with probability $\sin^2[(\phi_c - \phi_d)/2]$, meaning
that an error can occur. If the real secret is a hash function of $K$, $h(K)$, then even having a few errors at the input, the output will be very different from the correct one.

5. Polarization interferometer with Sagnac structure

The polarization interferometer has the same structure as a common interferometer but the beam splitters are replaced by polarization beam splitters. They have been used, for example, for error correction [16] and entanglement distribution [30]. Here we use it for implementation of a secure classical prisoners’ dilemma game. The optical setup used is shown in Figure 10.

Having the input state $\langle a|H\rangle + b|V\rangle \otimes (\alpha|H\rangle + \beta|V\rangle) \otimes (c|H\rangle + d|V\rangle) \otimes (\sigma|H\rangle + \delta|V\rangle)$, after some calculations one finds the following output state [30]

$$|\Psi\rangle_{1234} = aae\sigma|HHHH\rangle + bcd\sigma|VHVH\rangle + a\beta c\delta|HVHV\rangle + b\beta d\delta|VVVV\rangle + |\Omega\rangle,$$

where $|\Omega\rangle$ is the state containing terms with at least one output with zero photons. Hence, the quantum operation does not fail when there is one photon in each output. Moreover, having $c = d = \alpha = \beta = (\langle 0 | + |1 \rangle)/2^{1/2}$, the output state (6), when it does not fail, is $(\sigma|H\rangle + \delta|V\rangle)_{13} \otimes (a|HH\rangle + b|VV\rangle)_{24}$. This is the quantum state required for execution of the secure classical prisoners’ dilemma game. Once Alice and Bob share the two entangled states $(a\sigma|HHHH\rangle + b\alpha|HVHV\rangle + a\beta|VHVH\rangle + b\beta|VVVV\rangle)_{1234}$, measuring qubits 1 and 2, Alice will obtain the results: $|HH\rangle$ – both cooperate, $|HV\rangle$ – Alice cooperates and Bob defects, $|VH\rangle$ – Bob cooperates and Alice defects and $|VV\rangle$ – both defect. Due to the entanglements Bob, measuring qubits 3 and 4, will obtain the same results as Alice. This is the security, Alice cannot cheat Bob, and vice versa, because the result of their measurements are always the same. Table 1 is an example of the payoff table.

6. Conclusions

We have discussed the use of the Sagnac interferometer in quantum information technology. Four problems were discussed: interaction-free measurement, quantum key distribution, secret sharing and prisoners’ dilemma implementation. For the
interaction-free measurement we present two optical setups, the first having 25% of success and the second almost 100% of success per photon used. Both are easily implemented using common linear optical devices. Thus, our setups have the same efficiency as the other proposals found in the literature, but they are not equivalent to those in the sense that we have used another configuration (Sagnac) and only fiber-based devices. The QKD setup proposed is different from other proposals found in the literature since it is a one-way setup and, hence, it is more resistant against Trojan horse attack. Its disadvantage is the use of three SPDs and, since it uses single-photon polarization, it may be more suitable for short distance and high transmission rate QKD at 850 nm. Further, the QKD protocol is a little different from BB84 since Bob has to inform Alice of the bases used and if detection occurred in D_H or D_V detectors (any of them). At last, the proposed QKD protocol is well related to wave–particle behavior. We also provided an optical setup for secret sharing between five persons. The secret, which is not known by any user, can be read or used by one of the partners, named Fred, only if all the other four partners collaborate using their correct individual secret. The proposed setup is easy to implement, being basically a Sagnac interferometer with polarization diversity. Finally, an optical setup for implementation of secure classical prisoners’ dilemma was presented. The optical setup is constructed using two connected Sagnac polarization interferometers. Since the game requires entangled states and only linear optical devices are used, the optical setup is probabilistic.

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