Optimal fiber optic scheme for sub-SQL quantum receiver realization

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Abstract. Practical implementation of high-precision quantum measurements is an important problem in modern science. One of the main parts of the quantum receiver is the optical scheme. We developed and tested several optical circuits based on different types of interferometers, namely Sagnac-based scheme, Mach-Zehnder-based scheme, and Michelson-based scheme. All these schemes are assembled with optical fibers and fiber-optic components, since the fiber-optic implementation is closest to application in practical devices. Schemes were evaluated according to two main criteria: extinction and interference stability. On the basis of the obtained data, it can be concluded that the most suitable is the scheme based on the Mach-Zehnder interferometer. In continuous mode, we were able to obtain an interference extinction about 30 dB with acceptable temporal stability.

1. Introduction
Increasing the precision of optical measurements is an important task in many branches of modern science. Although the fundamental measurement precision limit (Helstrom bound) was determined back in the 60s of the last century [1,2], it has not been possible to approach it in practice so far. Traditional coherent optical receivers based on homodyne detection operate at the shot-noise limit, which leaves a clear gap in the error rate well above the Helstrom bound. To date, several strategies have been developed to improve the accuracy of signal measurement above the standard quantum limit (SQL) or shot noise limit [3-5]. One of the first, a strategy was proposed using optical displacement for complete nulling one of the states [2]. If the case of binary phase-shift keying (BPSK) is considered, the discrimination strategy is to null one of the states by adding an optical displacement of equal amplitude and different in phase by π. To realize the extreme accuracy of measurements in practice, it is necessary to have a high-efficiency single-photon detector integrated with a high-performance interference optical scheme [6-8]. In this article, we consider optical schemes that are potentially suitable for implementing a quantum receiver. All these schemes are based on optical fibers and fiber-optic components, since the fiber-optic implementation is closest to application in practical devices.

2. Experimental setups and methods
The efficiency of the optical scheme was evaluated according to two important characteristics. The first is high interference extinction. For this, it is necessary to achieve high mode matching and
eliminate external illumination and parasitic reflections. Second, high temporary stability, i.e. the receiver must maintain high performance for the longest time. There are certain specifics in working with fiber optic interferometers. It is the temperature expansion of the fiber, which results in phase instability and polarization distortions due to fiber deformation and refractive index change. Also, parasitic effects associated with vibration and acoustic exposure. To solve these problems, it is necessary to select the optimal interference scheme with a minimum set of fiber components. In this paper, we have considered three different interferometric schemes (figure 1).

Figure 1 (a, b, c). (a) Sagnac-based scheme; (b) Mach-Zehnder-based scheme, (c) Michelson-based scheme. PLS – pulse laser source, LS – laser source, D – detector, BS – beam splitter, PBS – polarization beam splitter, PC – Polarization controller, PS – phase shifter, DL – delay line, C – circulator, FM – Faraday mirror, OT – optical terminator

The signal and the local oscillator in the implemented schemes are obtained by dividing one source by the beam splitter. Sagnac interferometer (figure 1(a)) and Michelson interferometer (figure 1(c)) are based on single-mode (SM) fibers and components, Mach-Zehnder interferometer (figure 1(b)) is implemented on polarization maintaining (PM) optical fibers and components. DFB-lasers in a continuous (Michelson and Mach-Zehnder schemes) and pulsed mode (Sagnac scheme) were used as sources. LiNb phase shifters (PS) were used to change phase. The polarization controller (PC) in the scheme (figure 1(c)) was used to adjust the optical power balance in the arms of the interferometer. Circulators (C) and terminators (OT) in schemes (figure 1(a) and figure 1(c)) were used to prevent reflected light from getting back into the sources. The delay line (DL) was used to separate the signal and the local oscillator in time. As a detector (D) was used a semiconductor photodiode.

The extinction was calculated as the ratio of powers at the output of the interferometer with constructive and destructive interference. The interference maximum and minimum were adjusted by changing the phase in one of the arms of the interferometer using a phase shifter. To change the phase of the scheme of Mach Zehnder and Michelson, a DC voltage was applied to the shifter. In the Sagnac scheme, voltage pulses were applied to the modulator, and the period and duration of the pulses were calculated so that only the signal was shifted in phase and the phase of the locally oscillator remained unchanged.
To determine the stability of the interferometer, the time dependence of the power at the output of the interferometer was measured. Using the phase shifter, one of the operating points was found (constructive or destructive interference), and then the time dependence of the signal from the detector was recorded. The criterion for assessing the stability time was a change in power at the output of the interferometer by a factor of $e$. To increase stability, all circuits were located in an airtight box, and the fibers were reliably fixed to a metal plate. In order to increase stability, an active stabilization system with feedback [3] can be used, but in this paper, we consider only the passive stability of a specific optical scheme.

3. Results
Scheme based on the Sagnac interferometer (figure 1(a)). Due to the fact that the signal and the local oscillator pass through the same optical path, phase and polarization stability is achieved. For this scheme, we obtained a low extinction value (about 13 dB). This is due to the short coherence time of the pulsed source. The use of such a circuit is limited, since it only works in pulsed mode. This scheme is only suitable for demonstrating the principles of detection and in the classical form cannot be used in practical devices.

Scheme based on the Mach-Zehnder interferometer (figure 1(b)). It can operate both in pulsed and continuous mode. The use of polarization beam splitter at the input of the interferometer allows one to achieve high matching of optical powers in the arms of the interferometer. In continuous mode, we were able to obtain an interference extinction about 30 dB. To achieve acceptable temporal stability (few minutes), it is necessary to thermally and acoustically stabilize the circuit. The scheme looks promising for practical applications. However, a number of problems arise when working with this interferometer. The scheme requires the use of polarization maintaining optical fiber components, which increases the cost of the system. Rotations of polarization occur due to an imperfect connection of polarization maintaining fibers. Since the polarization rotates randomly in each of the arms of the interferometer, the polarization matching worsens.

Scheme based on the Michelson interferometer (figure 1(c)). The scheme, like the previous one, works both in pulsed and continuous mode. Using Faraday mirrors in each of the arms of the interferometer allows you to get rid of polarization distortions, which makes it possible to use conventional single-mode fiber. To achieve acceptable temporal stability, it is necessary to thermally and acoustically stabilize the circuit. This allowed achieving phase stability in time in a few minutes. In continuous mode, we were able to obtain an interference extinction about 23 dB. The main problem of this scheme is the tangible effect of the back reflection that occurs at the joints of the fibers. Even the use of FC-APC-type connectors does not completely eliminate the problem. This effect does not allow maximum extinction.

4. Conclusion
Based on the obtained results, the following conclusion can be made. The Sagnac scheme is highly stable, but is only suitable for demonstrating the principles of detection and is very limited for practical use. The Mach-Zehnder scheme has the best extinction (about 30 dB) and acceptable stability. This circuit is most suitable for the realization of the receiver with the highest sensitivity. A sub-SQL receiver based on this scheme has been recently realized [8]. Michelson-based scheme has medium extinction and acceptable stability, which makes it of a lower value for practical implementation.

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