Active and passive phase stabilization for the all-fiber Michelson interferometer

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Abstract. We put forward two methods for phase stabilization in the all-fiber Michelson interferometer. To perform passive phase stabilization, we use a heat bath for all fibers and electro-optical components, and put the interferometer in a hermetic case. To perform active phase stabilization, we monitor output power of the interferometer and develop an electronic feedback control. The phase stabilization methods enable stable interference pattern for several minutes, and can be helpful for the development of the optimal quantum receiver for coherent signals.

1. Introduction

Interferometry is a very useful technique of combining waves and observing the result of their interference in order to diagnose the parameters of interest that influence the interference pattern. This technique has numerous applications in physics, engineering, and applied sciences. For example, interferometry is recognized to be a crucial prerequisite in the field of ultimately sensitive detection of optical quantum signals. The signals can have very broad origin: from the extremely weak fluctuations caused by gravitational waves, to the long-haul classical and quantum telecommunication. The later case is mostly employed in optical fibers, hence the practical need to deal with the optical fiber interferometry.

One of the shortcomings of optical fibers is their high sensitivity to the external influences, such as mechanical stress, bends, or airflows. In order to build a practical device utilizing optical fiber interferometer, we need to reduce the interference instability and increase the stable operation time. A particular application that we have in mind is the development of the all-fiber optimal quantum receiver for weak coherent signals. The problem of optimal signal detection dates back to the late 60's, when quantum-mechanical properties of the signal were recognized as an unavoidable bottleneck for the ultimate measurement precision limit [1].

Traditionally, heterodyne or homodyne receivers are used to measure the phase and the amplitude of the signal without a priori knowledge of the signal parameters. Though in the simplest case, a receiver should be able to discriminate just two different signal states, e.g. coherent states with a fixed amplitude and binary modulated phase. In 1967 Helstrom found the theoretical limit for the maximum quantum signal detection precision, or the minimum signal detection error [1]. This limit is called the Helstrom bound, and a receiver able to attain this limit is called the optimum quantum receiver. The optimum quantum receiver has a higher signal detection precision compared to the heterodyne or homodyne receivers. Unfortunately, Helstrom did not propose a concrete realization of the optimum quantum receiver.
In 1973, Kennedy proposed a quantum receiver [2], which is based on the optical displacement of the input signal state and a single-photon detection. The Kennedy receiver exceeds the precision of the homodyne and heterodyne receivers in the limit of strong signals, but does not approach the Helstrom bound. Soon after the Kennedy’s proposal, Dolinar improved the scheme and shown the first proposal of an optimum quantum receiver [3], though his proposal is difficult to implement in reality. A more realistic approach to build the optimal quantum receiver was proposed only recently [4], which we plan to realize in the future. The Kennedy receiver is based essentially on the same principle (optical displacement of the signal and photon counting), but allows an easier implementation. Several proof-of-principle demonstrations of the Kennedy receiver and its slightly modified versions were already shown with help of the free-space interferometry [5,6]. However, the all-fiber realization of the Kennedy receiver has not yet been demonstrated.

We develop a Kennedy receiver based on the all-fiber Michelson interferometer. On the way to achieve the goal, we came across with some difficulties. The main difficulty of developing all-fiber interferometer is instability of the interference due to varying local temperature of a fiber, vibrations, polarization distortion, to name a few. To auto-compensate the polarization instability, we utilize the Michelson-Faraday interferometric scheme. Thus the phase instability remains the main challenge which we solve here. In this work, we show several technical solutions for passive and active phase stabilization of the Michelson interferometer.

2. Experimental setup and passive phase stabilization

We use a fiber-based DFB laser with 1548.7770 nm wavelength. The width of the spectrum is 2 MHz. The drift of central wavelength is negligible, due to the current and temperature stabilizations of the laser. The polarization is linear. Radiation is guided through the polarization controller PC1 on a polarization-dependent circulator C1, which is installed in a hermetic Box #1 (see Fig 1). The circulator plays the role of an optical isolator capable of transmitting radiation only in one direction from the laser to the interferometer. However, because of the reflections from the ends of the circulator, undesirable interference occurs, which leads to instability of the optical power at the input of the Michelson interferometer. On ports 1 and 2 of the circulator, two short SM-fibers were additionally added to stabilize the "parasitic" interference. At the input of the interferometer, a polarization controller PC2 is placed to adjust the polarization and improve the contrast. The Michelson interferometer consists of a 90/10 splitter BS1, two phase modulators PM1 and PM2, and two Faraday mirrors FM1 and FM2.

![Figure 1. Experimental setup. LD - Laser Diode at 1550 nm; PC1 and PC2 are the polarization controllers FPC031; C1 is a circulator; T1 and T2 are fiber light traps (terminators); BS1 and BS2 - beam splitters 50/50 and 90/10, respectively; PM1 and PM2 - phase modulators; FM1 and FM2 - Faraday's mirrors; Power meter Ophir VEGA with power head PD300-IRG-V1. Red line is fiber SMF-28e; Blue line - PM fiber; Black line - electrical wire.](image-url)
We use single-mode (SM) fibers in the Michelson interferometer. The behavior and analysis of multimode fiber interferometers are complex, because the multimode nature of the radiation creates more complex interference phenomena, which are very difficult to take into account and control. The characteristics of interferometers based on multi-mode fiber are much worse than ones based on SM fibers. Though even in the case of SM fibers, there is a number of problems associated with polarization phenomena in fibers. The polarization state of radiation in SM fibers can change rapidly and unpredictably due to external influences. Mismatch and fluctuations of the polarization state cause interference contrast fluctuations. Therefore, it is better to use polarization-maintaining (PM) fibers. In the case of employment SM fibers, we have to use reliable mechanical fixation of the fibers, which leads to a more stable polarization of the propagating radiation.

The main task of adjustment of the Michelson interferometer is phase difference stabilization between two arms. The delay phase $\varphi$ on a waveguide length $l$ is $\varphi = 2\pi \frac{n l}{\lambda}$, where $\lambda$ is radiation wavelength, $n$ is average index of refraction of the fiber core. The temperature instability of individual optical components is the main effect that influences the phase delay of the optical fiber due to changing refractive index of quartz and geometric parameters of the fiber (length and core diameter). The change of phase can be represented in the form $\delta \varphi = \frac{2\pi}{\lambda} \left( n \frac{\partial l}{\partial T} + 1 \frac{\partial n}{\partial T} \right) \delta T$. The first item is the contribution of geometric stretching. The second item is the contribution of changing index of refraction. The main contribution to the phase changing is the fluctuation of the index of refraction.

The phase sensitivity of the two-arm interferometer is $K = \frac{\delta \varphi_2 - \delta \varphi_1}{\delta T} = \frac{2\pi}{\lambda} \frac{\partial n}{\partial l} \Delta l$. Where $\Delta l$ is difference length of two arms. To reduce phase sensitivity, we should use arms of the interferometer with equal lengths ($\Delta l = 0$). The arms of the interferometer should be in the same external physical conditions, so that the phase sensitivities of fiber arms are the same. But, in reality, it is difficult to achieve equality of the arms. Thus the contribution of temperature fluctuations can be significantly reduced, but does not disappear.

An additional influence on the interference stability is the mechanical stress on the fibers and on the joints of the interferometer connectors: air convection, acoustic waves, pressure, mechanical vibrations transmitted from the table, etc. To ensure the same physical conditions for the arms of the interferometer, the optical elements of the Michelson interferometer are fixed by means of a sticky aluminum tape to a massive brass plate, which has the role of a thermal bath. The plate is placed in a hermetic metal Box #2. The electrical contacts of the phase modulators are connected to the case. For additional shielding against thermal radiation, the Box #2 is wrapped in aluminum foil and in a dense black textile and placed on four bolts fastened to the optical table. The bolts act as anti-vibration mounts that reduce mechanical vibrations coming from the optical table. The polarization controller PC2 is placed at the input of the interferometer for adjusting polarization.

![Figure 2](image-url) Output optical power from the Michelson interferometer as a function of voltage on the phase modulator PM2.
We supplied the phase modulator PM2 by voltage from 0 to 5.1 V for the interference contrast measurement (see Fig. 2). The minimum output power is 0.57 uW, and the maximum output power is 60.3 uW, which correspond to the phase difference of 0º and 180º between the arms of the interferometer, respectively. In this case we achieve the interference contrast \( C = \frac{P_{\text{max}}}{P_{\text{min}}} = 106. \)

**Figure 3(a,b).** Phase (a) and contrast (b) instability of the Michelson interferometer.

### 3. Active phase stabilization

After performing the passive phase stabilization, we obtain the slow-varying drift of the interference pattern (see Fig. 3a). To achieve high interference contrast (more than 100), we have to manually adjust the phase difference by the phase modulator PM1. Then the task of the interference stabilization can be formulated not as "What should be done to make the phase difference between the arms of the interferometer constant?", but rather "What should be done to change the phase difference as slowly as possible?" We obtain the stabilization of interference contrast by all the above methods of passive phase stabilization on a timescale of a few minutes (see Fig. 3b). This turns out to be enough for employing the active phase stabilization system. We use a feedback control in the Michelson interferometer for active phase stabilization. To do this, the output of the interferometer through the BS2 beam splitter is applied to the Ophir VEGA power meter with the PD300-IRG-V1 detector head. From the power meter, an analog signal carrying the voltage amplitude, which directly proportional to the measured optical power, is fed to the hardware platform "Arduino Uno". After the signal processing, the platform supplies the needed voltage to the phase modulator. The maximal phase adjustment rate is about 70 ms. The rate is limited by the detector head rate. After the active phase stabilization, we can maintain the required phase difference between two arms of the Michelson interferometer for much longer time far exceeding the data acquisition time of the quantum receiver.

### 4. Conclusions

We developed passive and active methods for the phase stabilization in an all-fiber Michelson interferometer that operates at the conventional telecom C-band (1550 nm). The methods extend the stable operation time for sufficiently long period and can be used for the development of the all-fiber optimal receiver for coherent signals [4].

### 5. Acknowledgement

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