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Introductory Chapter: Chromatic Dispersion Monitoring in Synchronization Channel of Quantum Key Distribution Systems with Carrier Modulation Coding

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1. Introduction

The method of quantum key distribution (QKD) with carrier modulation coding (CMC) was proposed in [1, 2] and developed in [3–8]. Its advantages are the ease of input and coordination of the optical phase, the high data transfer rate, the fundamental possibility of frequency multiplexing of the signal, as well as the simplicity of constructing a consistent scheme. The main difference lies in the fact that in the QKD-CMC systems, the quantum signal is not generated directly by the source but is carried to side frequencies as a result of phase, amplitude modulation, or a combination of these. In the latter works, to each state of the photons, instead of the amplitude or phase of the modulating signal at a certain frequency, one or more lateral component frequencies either photon optical carrier [9, 10] are put into line. We in [11–13] present a universal system capable of realizing all the mentioned types of modulation transformation and the new one based on tandem amplitude modulation and phase commutation with partially or full suppressed carrier.

Alice and Bob's synchronization channel provides frequency and phase matching of the modulating signals. The deviation of the phase of the modulating signal from the base position during the re-modulation of the signal spectrum at Bob leads to a change in the radiation power at the side frequencies. A phase setting error, at the same time, reduces the visibility of the interference pattern and increases the level of quantum bit errors in the signal. The values of the optical signal-to-noise ratio (OSNR) in the system are also determined by the accuracy of setting the amplitude of the modulating signals of Alice and Bob.

The changing ambient temperature and chromatic dispersion (CD), in turn, depending on temperature, introduce an additional time-varying phase delay of the synchronization signal, which leads to a phase mismatch. In [14] it is shown that the correction of the clock phase should be carried out every 2–3 seconds to eliminate the influence of temperature and 2–3 hours to correct the effect of CD. If we take into account that CD itself can change both with a change in the temperature of the fiber and with a change in its configuration, we should speak about the need for its constant monitoring.

Problems of maintaining the phase and amplitude in the synchronization channel arose in the author's Microwave Photonics Lab., KNRTU-KAI, Kazan, when trying to create a QKD-CMC system model on a fiber wound on a reel and connected in a total length of 24 km. Similar problems have arisen for our colleagues from ITMO, Saint-Petersburg, and the Kazan Quantum Center, KNRTU-KAI, Kazan, when they built quantum systems at distances of several kilometers of the real network of JSC "Tattelecom" operator, Kazan. However, 100 km is the limit that is not yet successfully overcome. At greater distances, individual photons are simply absorbed by the fiber-optic transmission medium. The main problem for long-haul quantum cryptography is loss. It should be noted that today the project of the longest in Russia Kazan-Chistopol line, which is 160 km long, is being created at ITMO and KNRTU-KAI, which will undoubtedly face the problem of monitoring chromatic dispersion.

Due to the natural symmetry of modulated coding and the highest achievable ratio of the modulation conversions, amplitude-phase modulation with complete or partial suppression of the optical carrier has found a particularly wide application in the systems of microwave photonics [15–22]. Let us apply results of given papers and microwave photonic principals [23, 24] to design CD monitoring principles for synchronization channel of QKD-CMC systems.

We'll present the results of the radio-frequency clock signal (RFCS) method, chosen by us as the most simple in implementation and promising, for CD monitoring in high-speed and extended communication channels. The basic measurement error is determined by the level of variation of the laser power and the polarization-mode dispersion (PMD). The last successful implementation of the RFCS method uses the built-in Bragg notch filter (BNF) on the carrier frequency and calculating the ratio of the RFCS powers in the filtered and unfiltered branches of the measurement channel. It made possible to achieve CD measurements in the range from 0 to 200 pm/ns and increase their sensitivity to 0.12 dB/(ps/nm) regardless of the PMD presence [25].

However, the stability of the central wavelength of the BNF position, due to the change in environmental parameters, and the noise characteristics of the synchronization channel, became a significant influence on its results. For dynamic range of CD measurements near 30 dB, the error from the instability of the central BNF wavelength is ± 1.5 dB, when a temperature change is $\pm 1^\circ\text{C}$. It is also shown in [25] that the monitoring scheme becomes inoperable, when OSNR of measurements is less than 15 dB.

The main chapter is based on the materials of Morozov et al. (2010–2018) papers [11, 15–22] and additional and new results of theoretical and experimental researches in QKD-CMC theme [12, 13], so as direct [26] and miscellaneous applications [27–30]. The next chapter sections are organized as follows. The second section shows the poly-harmonic principles of BNF position central wavelength monitoring. The third section discusses OSNR gain determination in different cases of poly-harmonic probing. In conclusion, the received results are analyzed, and the key development challenges for CD monitoring in synchronization channel are highlighted.

2. Poly-harmonic principles of BNF central wavelength monitoring

In this section, we propose a microwave photonic method for monitoring CD in synchronization channel based on analysis of the BNF reflectance spectrum position. As the prototype of the CD measurement system, the methods described in [25, 26] were taken. A monitoring subchannel based on the analysis of the optical carrier signal reflected from the BNF was included in the method operation

sequence. Before reflection, carrier of synchronization channel of QKD-CMC system is modulated by amplitude at the $f_{CL}/100$ frequency in the data generation stage, where f_{CL} is the frequency of the clock synchronization signal (1–10 GHz). The presence of modulated components allows probing the position of the BNF, tuned by the center to the optical carrier, and produces a mismatch signal for its detuning, in analogy with the microwave photonic method of FBG interrogation, presented by us in [27]. In the given paper, symmetrical two-frequency probing signal was used. We additionally consider the methods of amplitude-unbalanced three-frequency and symmetrical four-frequency probing. In [26] the possibility of OSNR increasing till 10–12 dB, when signal processing realized on frequency-modulated components beating envelope, was shown also for full telecommunication channel. We shall reanalyze these results from the point of our task view. We defined the parameters, which could be used for registration in monitoring system, and carried information about interaction between double-, three-, and four-frequency probing oscillations and BNF.

2.1 Two-frequency symmetrical probing

Symmetric double-frequency probing radiation is a complex signal with amplitude and phase modulation. The main feature of this signal is that all of its components (instantaneous envelope $A(t)$, phase $\theta(t)$, and frequency $\omega(t)$) depend on its component amplitude ratio A_1, A_2 . We evaluated the modulation rate of double-frequency signal. Thereto we will use the modulation coefficient:

$$m = 2(A_{\max} - A_{\min})/2(A_{\max} + A_{\min}), \quad (1)$$

where A_{\max} is sum of A_1 and A_2 , and A_{\min} is its difference.

Calculation results for $m(\delta)$, where δ is referenced BNF detuning, are shown in **Figure 1** for different (A_1/A_2) .

We also defined the phase gradient of double-frequency signal under it components amplitude changing. Calculation results of $\theta(\delta)$ are shown in **Figure 2** for different (A_1/A_2) .

Analysis of the dependences $m(\delta)$ and $\theta(\delta)$ allows determination of BNF central wavelength shift, according to δ , during the measurement of modulation index m and phase θ of probing signal components A_1 and A_2 beating envelope.

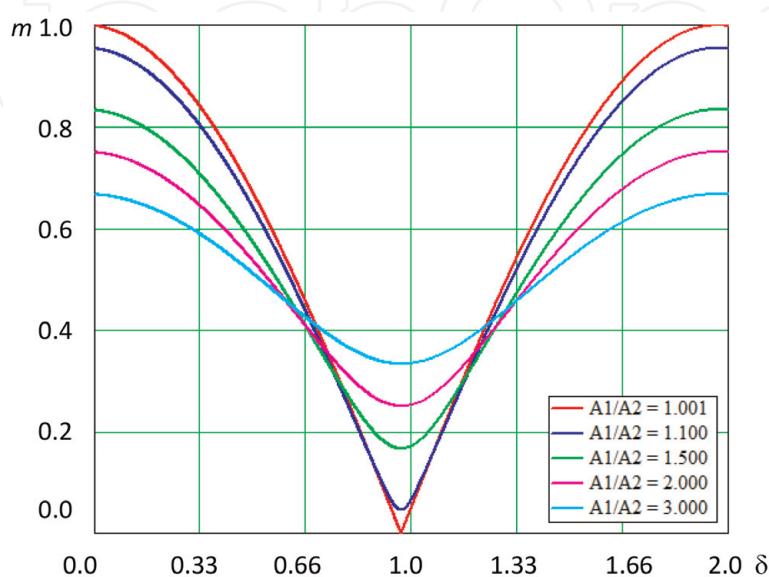


Figure 1.
 Dependence $m(\delta)$ for different (A_1/A_2) .

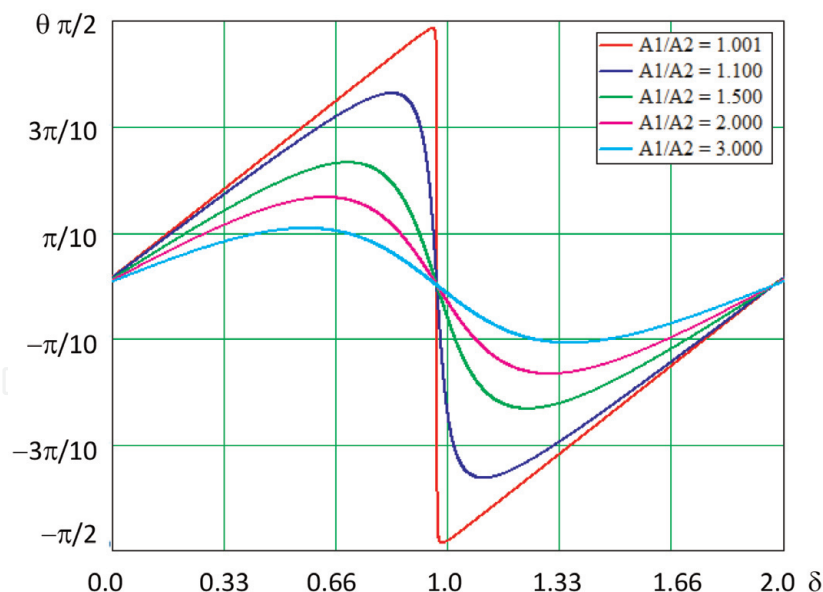


Figure 2.
Phase shift dependence $\theta(\delta)$ on component amplitude ratio A_1/A_2 .

Produced on amplitude modulation coefficient or phase changing mismatch signals use to make correction in CD monitoring process or retuning the center wavelength of BNF.

2.2 Three-frequency symmetrical amplitude-unbalanced probing

It is known from a number of works that two-frequency probing, as simplest, does not always allow one to unambiguously determine the direction and magnitude of the BNF central wavelength shift from the wavelength of the carrier [28, 29]. Let us set the task of determining the position of the BNF central wavelength based on a three-frequency amplitude-unbalanced probing, relying only on the data coming from the photodetector PD to the ADC. Without changing the position of the carrier frequency of the probing radiation, we will shift the BNF in the range. For each position of the BNF, we analyze the parameters of the low-frequency signal at the output of the photodetector, tuned to determine the amplitude of the oscillations at the direct current (DC), the probing frequency $f_{CL}/100$, and the doubled frequency $2f_{CL}/100$. The characteristics of the reflected signal level calculated from the three-frequency probing procedure on DC, 100 and 200 MHz for the central frequency position and detuning, are shown in **Figure 3**.

Taking into account the position of the BNF relative to the carrier, we can say analogically [31] that we reduce the error in the CD measurement by 10% (3 dB).

2.3 Four-frequency symmetrical probing

Two pairs of probing signals shifted from the carrier are sent to the mediums of the left and right slopes of BNF. Bragg wavelength of BNF is equal to the carrier wavelength; different frequency inside pair is equal to 100 MHz. The outputs of photodetector signals are formed, corresponding to the beating of the first (channel 1) and second (channel 2) signal pairs [20, 30]. By measuring the difference between amplitudes of each beating envelope, one can unambiguously determine detuning sign and value of central BNF wavelength.

Three cases of DNF deviation are shown in **Figure 4**.

In the first point, the BNF offset from the resonance wavelength is absent, and the output amplitudes of beating envelopes are equal.

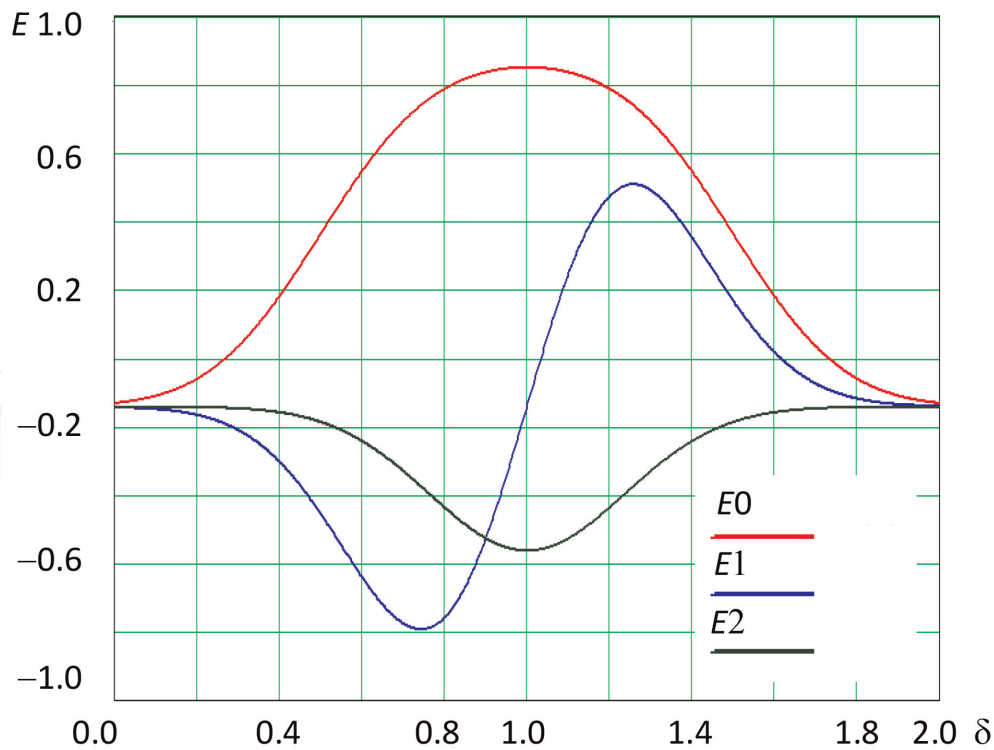


Figure 3.
 Components reflected from BNF and their levels calculated for the three-frequency probing radiation at central (carrier) position and its detuning.

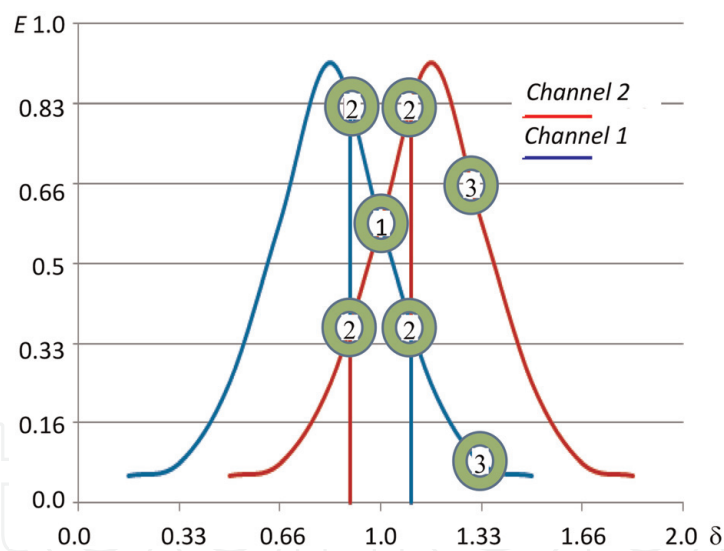


Figure 4.
 Three cases of BNF deviation for four-frequency method.

In the second point, there is a slight BNF deviation, and the direction and magnitude of the deviation are determined by greater amplitude of beating envelopes.

In the third point, there is a significant deviation, and the direction and magnitude of the deviation are determined by the presence of a signal of beating envelopes and its level in one of the channels.

3. OSNR problem for CD monitoring in synchronization channel

For experimental part, we chose three-frequency method, as less compliant in comparison with four-frequency one. The procedure for monitoring the position of

the BNF in synchronization channel can be implemented to RFCS method realization structure. In this case, it contains one narrowband photodetector with a 10 GHz band and filters tuned to frequencies at 0, 100 and 200 MHz from the carrier with a bandwidth of 10 MHz. The procedure for such analysis relates to in-line monitoring procedures, and the arrangement of frequency components at a frequency of 100 MHz from the frequency of the RFCS allows us to speak about identical for all three constituent CD parameters and the corresponding identical change in their amplitudes as it increases or decreases.

Using the algorithm for approximating BNF spectrum by the Gaussian curve at each measurement makes it possible to increase the accuracy of determining its central wavelength by an order.

Without going into the details of the physical nature of the phenomena, the level of the main noise of the photodetectors is higher than the level of background noise of scattering in the fiber and elements of the installation and determines the possibility of detecting the received signal (**Figure 5**). The gain in improving the OSNR in comparison with single-frequency measurements on the RFCS is determined by the following expression [15–20, 27]:

$$G = \left[\int_0^{BW_{PD}} S \right] / \left[\int_0^{BW_3} S + \int_{\frac{f_{CL} - BW_3}{100}}^{\frac{f_{CL} + BW_3}{100}} S + \int_{\frac{2f_{CL} - BW_3}{100}}^{\frac{2f_{CL} + BW_3}{100}} S \right], \quad (2)$$

where $S = S(f)df$ is the spectral noise density of the receiver, BW_{PD} is the bandwidth of the PD equal to 10 GHz, and BW_3 is the frequency band of filters (10 MHz) at frequencies of 0, 100–200 MHz.

The gain is determined by the different filter bandwidth, nature, and noise level in different frequency regions $S(f)$ for different types of photodetector (with bandwidths 10 GHz) and filters (with bandwidths 10 MHz), respectively. In filter regions near 100 and 200 MHz, there are only thermal and shot noises. Current noises are characterized only for narrow DC filter. Taking into account the given data, the gain in OSNR can be 10–12 dB.

Thus, when using in-line CD monitoring with a preliminary amplitude modulation of the RFCS, the gain relative to the OSNR compared to the monitoring

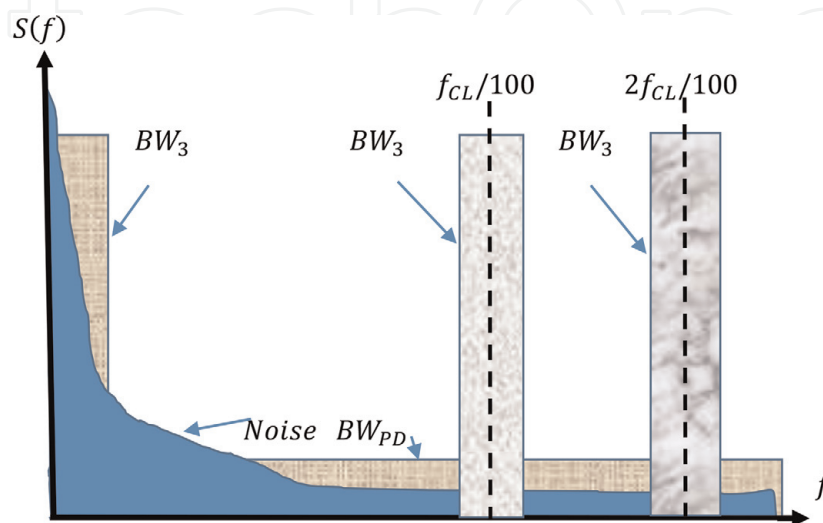


Figure 5. Illustration for OSNR gain catch for three-frequency probing method: Noise—spectral characteristics of noise for photodetector realizations bandwidth BW_{PD} . Three-frequency probing method has complex gain parameters and characterizes only by one disadvantage of large current noise filtering on DC component.

at one frequency of the RFCS can be 10–13 dB. Thus, CD analysis on the RFCS can be carried out, starting with the classical OSNR in 3–5 dB.

4. Conclusion

We demonstrated a microwave photonic method for CD monitoring of a high-speed synchronization channel based on analyzing the reflectance spectrum of the built-in BNF with the preliminary amplitude modulation of the optical carrier and the RFCS method. The results of the simulation show that the proposed method of in-line monitoring makes it possible to determine the magnitude and direction of the filter shift by poly-harmonic probing. Thus, taking into account its position relative to the carrier, we will reduce the error in classical CD measuring which is usually equal to 10%/°C (1.5–3 dB). When using in-line CD monitoring with the preliminary amplitude modulation of the RFCS, the gain relative to OSNR compared to the monitoring at carrier frequency can be 10–13 dB. Thus, CD analysis by the RFSC method can be performed starting from the classical OSNR of 3–5 dB.

The application of such type monitoring methods for QKD-CMC system will allow us to suggest an even wider use in the transition to homodyne and heterodyne systems. It should be noted that their development is still carried out at a theoretical level and does not take into account the fact that with an increase in the length of telecommunication lines, the probability of increasing the influence of CD on the phase value of the coded components will increase significantly.

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