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Quantum state preparation with optical injection: Issue of intersymbol interference

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Abstract. The dependence of the modulating signal on its history, which is referred in the literature to as intersymbol interference, may significantly affect the security of quantum key distribution. Here, we investigate the issue of intersymbol interference in the context of quantum state preparation with pulsed optical injection. Both experimental and theoretical study are presented.

Keywords: quantum key distribution, semiconductor lasers, pulsed optical injection, intersymbol interference

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Приготовление квантовых состояний с помощью оптической инжекции: проблема межсимвольной интерференции

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Аннотация. Зависимость модулирующего сигнала от его предыстории, называемая в литературе межсимвольной интерференцией, может существенно влиять на безопасность квантового распределения ключей. Настоящая работа посвящена вопросам межсимвольной интерференции в контексте подготовки квантовых состояний с помощью импульсной оптической инжекции как на основе теоретического анализа, так и в плане экспериментов.

Ключевые слова: квантовое распределение ключей, полупроводниковые лазеры, импульсная оптическая инжекция, межсимвольная интерференция

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Introduction

Various methods of state preparation for quantum key distribution (QKD) have been proposed in the literature. One of the most promising techniques is based on the use of optically injected semiconductor lasers [1–4], where the master is used as a phase preparation laser, and the slave is used as a pulse preparation laser. This method allows performing both phase and time-bin encoding, which makes it quite flexible. Moreover, a pulsed laser subjected to optical injection exhibits reduced chirp, suppressed relaxation oscillations and, consequently, provides improved laser pulse interference.

Here, we address the problem of intersymbol interference in case of quantum state preparation with optical injection. Both experimental results and simulations are provided, and possible solutions of the problem are discussed.

Materials and Methods

For the experiment, we used a couple of distributed feedback lasers connected via an optical circulator as shown in Fig. 1. A variable optical attenuator was installed in front of the slave laser to control the injected optical power. Both lasers operated in a gain-switching mode at wavelengths 1549.3 nm (master) and 1550.6 nm (slave). A WDM filter centered at 1549.32 nm (C35) was placed at the output of an optical circulator. Due to optical injection locking, the wavelength of the slave laser was shifted towards the master's wavelength when the pulse from the master came into the slave's cavity. Thereby, only those slave laser pulses whose frequency has been shifted by the master passed through the WDM filter (see Fig. 2).

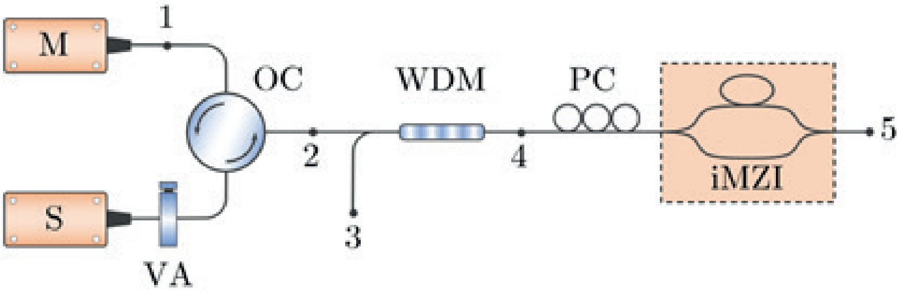

Fig. 1. The scheme of an experimental setup. M and S stand for master and slave lasers, VOA – variable optical attenuator, OC – optical circulator. PD –photodetector, PC – polarization controller, iMZI – integrated Mach-Zehnder interferometer. Optical signal was detected from points 1–5

The slave laser emitted short pulses at repetition rate of 1.25 GHz, whereas the master laser emitted two types of signals: short pulses with a duration of approximately 400 ps, and long pulses, which were approximately double the duration of short pulses. Short master pulses were used to prepare states in the Z-basis: when the pulse appeared in the early time slot, we assigned a bit value '1' to it (the Z_1-state), and when the pulse appeared in the late time slot, we assigned a bit value '0' to it (the Z_0-state). In the X-basis, we prepared only one state (X_0) by selecting the modulation current such that there is a phase difference $\Delta\varphi = 0$ between the corresponding pair of pulses.

Prepared quantum states were controlled with the thermostabilized integral imbalanced Mach-Zehnder interferometer (iMZI) with the delay line of 800 ps. In front of the interferometer, we installed a polarization controller to fine-tune the polarization state of the incoming signal. A Thorlabs PDA 8GS photodetector was used for the optical signal detection.

Results and Discussion

Experimental results on the state preparation using pulsed optical injection are shown in Fig. 2. Optical signal of the maser laser presented in Fig. 2, *a* was detected at point 1 of the optical scheme (see Fig. 1) and corresponds to the following cyclically repeated sequence of states: X_0, $\varnothing$, Z_1, X_0, Z_0, X_0, Z_1, $\varnothing$, where the “empty” state, $\varnothing$, was inserted intentionally. Significant distortions that can be clearly seen in the shape of master pulses are related to imperfections in the electrical signal from the driver. However, we note that this signal shape was quite stable (signal variations are highlighted in Fig. 2, *a* in yellow). It is also clear from Fig. 2, *a* that the shape of master laser pulses heavily depends on the prehistory, i.e. on which of the four states (Z_0, Z_1, X_0, or $\varnothing$) preceded the current pulse. Such dependence is generally referred to as intersymbol interference [5, 6].

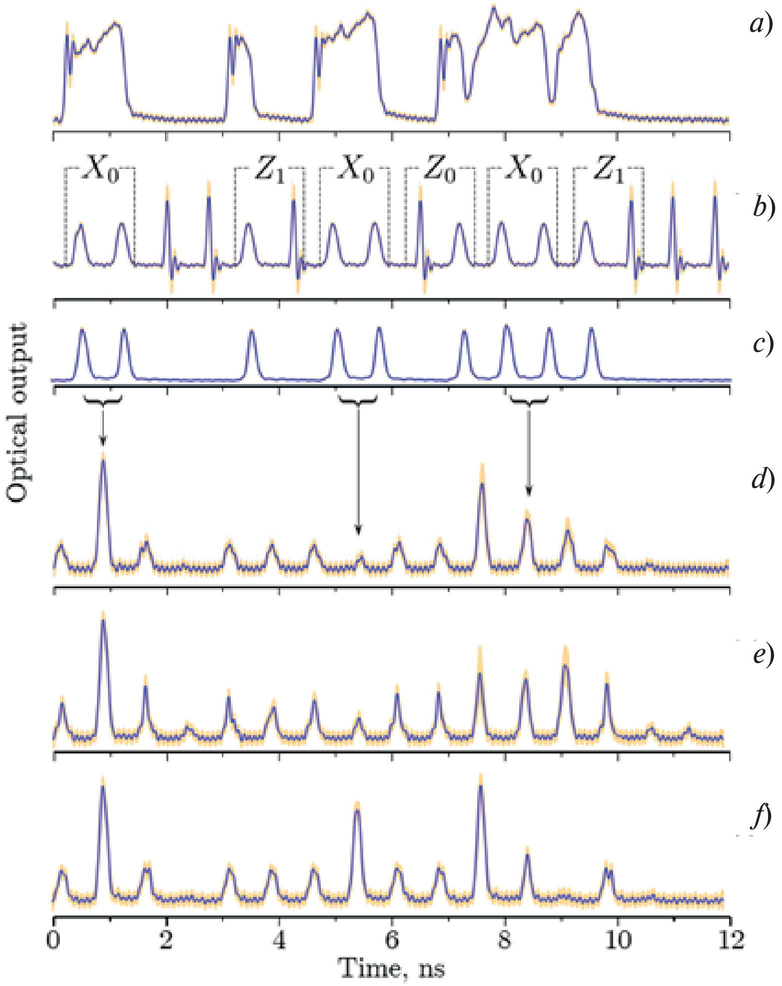

Fig. 2. Pulses emitted by the master laser (*a*), pulses that are coming out of the optical circulator (*b*), slave laser pulses that are coming out of the WDM filter (*c*), the result of the interference with different I_p values (*d*, *e*, *f*)

Figure 2, *b* demonstrates a sequence of slave laser pulses that corresponds to the master signal shown in Fig. 2, *a*. (This signal was recorded at point 2 of the scheme in Fig. 1.) One can see that pulses generated in the absence of optical injection are notably different from pulses appearing under emission of the master laser (the former are shorter and have a higher amplitude). Figure 2, *c* shows the same pulse sequence as in Fig. 2, *b* but recorded after the WDM filter at point 4 of the scheme. One can see that pulses of the slave laser emitted in the absence of master radiation are effectively filtered out. It is important to note that the shape of laser pulses in Fig. 2, *c* does not actually depend on the shape of master pulses, which means that intersymbol interference is less pronounced in the slave laser signal. Note, however, that this is true only for the *Z*-basis (see below).

Figures 2, *d*, *e*, *f* show the pulse sequences, corresponding to the interference of pulses from (Fig. 2, *c*) in the interferometer with the delay line of 800 ps. In (Fig. 2, *d*), the peak-to-peak value of the modulation current, I_p, was 34.4 mA; in (Fig. 2, *e*) and (Fig. 2, *f*) the value of I_p was set to 17.2 and 51.6 mA, respectively. Pulses that were "decoded" from X_0 states are marked with arrows. It can be seen that the intensity of the interference pulse is different in different places of the pulse sequence, which is due to intersymbol interference in the master signal. Thus, although the dependence of the shape of master pulses on the signal history does not seriously affect the shape of slave laser pulses in the *Z*-basis, it causes the significant intersymbol interference in the *X*-basis.

There are two possible reasons for the intersymbol interference in (Fig. 2, *a*). The first one relates to purely technical issues due to inaccuracies in laser driver design that lead to impedance mismatch in different parts of the electrical circuit. A more accurate design for the laser driver is required to remedy this issue. The second reason is purely physical and deals with the finite lifetime of carriers in the active layer of the laser diode. To check the latter impact, we have performed simulations of laser dynamics for the system shown in Fig. 1. Results are summed up in Fig. 3.

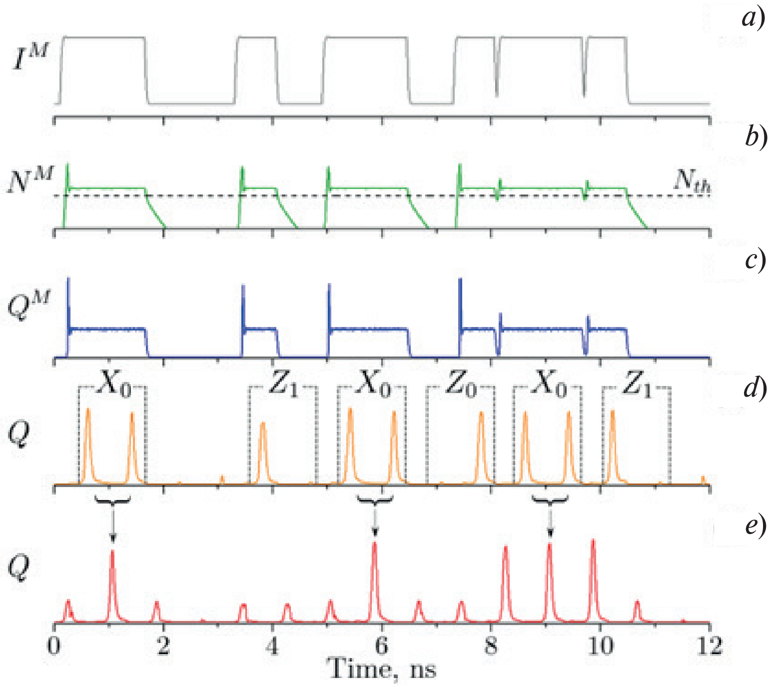

Fig. 3. Simulations of the sequence of quantum states. The master laser electric signal (*a*), charge carrier number dynamics (*a*), pulses coming from the master laser (*b*), slave laser pulses that are coming out of the WDM filter (*c*), the result of the interference (*d*)

We have used a standard model of stochastic rate equations [2] with the following set of laser parameters: master laser photon lifetime τ_{ph} = 1.0 ps, slave laser photon lifetime τ_{ph} = 2.0 ps, electron lifetime τ_e = 1.0 ns, quantum differential output η = 0.3, transparency carrier number N_{tr} = 4×10^7, threshold carrier number N_{tr} = 5.5×10^7, spontaneous emission coupling factor C_{sp} = 10^{-5}, confinement factor Γ = 0.12, linewidth enhancement factor α = 5, master gain compression factor χ = 30W^{-1}, slave gain compression factor χ = 20W^{-1}, master-slave detuning $\Delta\omega/2\pi$ = 100 Hz. Figure 3, *a* shows the electrical signal $I^M(t)$ simulating the master's pump current, Fig. 3, *b* demonstrates time evolution of the carrier number $N^M(t)$ corresponding to this driving signal, Fig. 3, *c* depicts the master laser output intensity $Q^M(t)$, and Fig. 3, *d* shows the output intensity of the slave laser after spectral filtration (WDM filter was modelled with a second-order Butterworth filter). Finally, Fig. 3, *e* shows the result of the slave laser signal interfering with itself after an 800 ps shift.

In the above simulations, the dependences $Q^M(t)$ and $N^M(t)$ in the interval from 7 to 11 ns, which correspond to the sequence of states Z_0, X_0, Z_1, deserve attention. Here, the delay between different master pulses is so small that the carrier number does not have enough time to fall considerably below threshold. Therefore, the master laser keeps operating in a quasi-continuous regime, and the laser pulses in the neighboring states turn out to be correlated in phase, which may lead to information leakage. However, this does not lead to significant distortions of the master signal and, consequently, to errors when encoding/decoding the signal in the *X*-basis. Therefore, we can conclude that the state preparation inaccuracy caused by the intersymbol interference shown in (Fig. 2, *d*, *e*, *f*), relates exclusively to inaccuracies in laser driver design.

Conclusion

We have demonstrated the case of intersymbol interference that occurs during optical-injection-based encoding. We also showed that the main cause of intersymbol interference in our case are inaccuracies in laser driver design. One of the possible solutions to minimize this effect (in addition to more accurate driver design) is to decrease the pulse repetition rate for the master laser.

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