High extinction ratio integrated optical modulator for quantum telecommunication systems

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Abstract. A method for increasing the extinction ratio of integrated optical Mach-Zehnder modulators based on LiNbO\textsubscript{3} via the photorefractive effect is proposed. The influence of the photorefractive effect on the X- and Y-splitters of intensity modulators is experimentally studied. An increase in the modulator extinction ratio by 17 dB (from 30 to 47 dB) is obtained. It is shown that fabricated modulators with a high extinction ratio are important for quantum key distribution systems.

1. Introduction
One of the most widely spread materials in modern integrated optics is lithium niobate (LiNbO\textsubscript{3}) \cite{1, 2}, which is used as a wafer for different devices because of its transparency in the visible and near infrared spectral regions \cite{3}, the presence of the electro-optical Pockels effect \cite{4}, and the applicability in nonlinear optics \cite{5}. Moreover, there are technologies of fabrication of stable optical waveguides on lithium niobate with low losses and the mode sizes suitable for coupling to standard single-mode optical fibers \cite{1, 2}.

After the birth of quantum information science, lithium niobate waveguide architectures emerged as one of key platforms for enabling photonics quantum technologies. However, new photonic systems place new demands on characteristics of integrated optical devices. This paper is devoted to the Mach-Zehnder (MZ) intensity modulator with an improved extinction ratio which is important for quantum key distribution systems \cite{6}.

2. Mach-Zehnder intensity modulator
The Mach-Zehnder intensity modulator is based on a Mach-Zehnder waveguide interferometer \cite{4}. This device consists of an input waveguide and an X- or Y-splitter, which divides the input optical power into two interferometer arms. An electric field applied to the waveguide arms through electrodes induces a phase difference between the waves in the arms via the Pockels effect. The second X- or Y-splitter brings the optical waves together and the result of interference exits through the output waveguide (figure 1).

In the ideal case, the modulator transmits the maximal power if the signals from the interferometer arms are in phase and transmits no power if the signals are out of phase. However, in a real MZ modulator the difference between the maximal and minimal transmitted power is smaller because of finite tolerances of fabrication processes, and, first of all, because of a finite photolithography resolution. A typical extinction ratio (i.e., the ratio between the maximal and minimal transmitted...
powers) of commercially available MZ intensity modulators lies in the range 20–30 dB. Since the precision of fabrication cannot be increased, the ways for correcting the waveguide elements that have already been fabricated should be investigated.

![Figure 1. Integrated MZ intensity modulator](image)

One of the ways is to use photorefractive properties of lithium niobate. Due to the photorefractive effect, a local irradiation of its surface can cause a decrease in the refractive index. The maximal value of such a decrease can be about $10^3$ [7], while the refractive index increase of the waveguides on LiNbO₃ is about $10^{-2}$-$10^{-3}$ [1], so the photorefractive effect can be used for correction of waveguide elements. Such a possibility was demonstrated experimentally.

3. Experiment
The experimental setup used for the photorefractive waveguide correction is presented in figure 2. A local irradiation of the lithium niobate wafer was performed with the help of a He-Ne laser (633 nm, 4.5 mW), the light from which was directed through a standard single-mode optical fiber. The light spot positioning on the integrated optical scheme was performed by a 3-axis translation stage (figure 2).

![Figure 2. Experimental setup.](image)

The correction of optical waveguide splitters of two types (X and Y) was investigated. The dependence of the change in the splitting ratio on the light spot position was measured (figures 3, 4).
During the correction of the Y-splitter the light spot was placed on the arms of the splitter, for the X-splitter the light spot was on the lines perpendicular to the waveguides.

![Diagram of light spot position and splitting ratio change](image)

**Figure 3.** Splitting ratio change versus light spot position (Y-coupler).

A typical time of irradiation for reaching the steady state condition was about 2 minutes and was in agreement with the photorefractive response time. A homogeneous illumination of the chip with an intense visible or UV light erased the local refractive index change and returned splitters to the initial states.

The measured dependencies presented in figures 3 and 4 show that there are regions of the splitters which are sensitive to the photorefractive correction. The light spot position corresponding to the maximum splitting ratio change depended on the light distribution between coupled waveguides in the X-coupler. For the parallel section of the X-coupler the spot was in the mid position between the waveguides and shifted towards the waveguide with a higher intensity in the input (converging) and output (diverging) sections of the X-splitter. For the Y-splitter the influence of the photorefractive correction on the arms lead to opposite changes in the splitting ratio (see figure 3).

After the experiments with individual X and Y power splitters, the possibility of photorefractive correction was studied for the Y-couplers included into a MZ modulator. The extinction ratio measurements for such a corrected modulator showed an increase of 17 dB (from 30 to 47 dB).
4. Conclusions
The results obtained show that the photorefractive effect can be used for correcting the splitting ratio of X- and Y-power splitters and, therefore, for increasing the MZ modulator extinction ratio. Modulators with an increased extinction ratio are promising for applications in quantum key distribution systems [6].

The dependences measured in the experiments show the regions of the power splitters most sensitive to the correction and can be used in further investigations of other methods of correction, such as photorefractive correction with thermal fixing [8] or intense femtosecond laser writing [1].

References
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Figure 4. Splitting ratio change versus light spot position (X-coupler).