Shorted saturable absorbers to enhance extinction ratio in QKD transmitter chips

J. Konig, M. J. R. Heck, X. J. M. Leijtens

Eindhoven University of Technology, Eindhoven Hendrik Casimir Institute, PO Box 513, 5600MB Eindhoven, The Netherlands

The extinction ratio of modulators in quantum key distribution (QKD) transmitters has a significant influence on the quantum bit error rate. In simulations and measurements, we demonstrate that adding an electrically shorted saturable absorber (SA) behind the modulator of a photonic-integrated QKD transmitter chip can increase the extinction ratio of the modulator by up to 10 dB. This paves the way for significantly lower quantum bit error rates when using these transmitters. Because it is shorted, the SA becomes a simple building block, with no need for additional signal inputs. The extra losses in the signal induced by the absorber are irrelevant to the QKD transmitter performance (for both continuous variable and discrete variable QKD transmitters) because the pulses will be attenuated to low photon numbers after the modulation.

Introduction

The extinction ratio of a modulator defines the power difference between the on and off states in an optical signal, affecting the bit error rate in photonic transmitter chips [1]. Improving the extinction ratio typically requires additional active components [2]. In QKD systems that work with attenuated lasers (for both continuous variable (CV) and discrete variable (DV) QKD), the signal after the modulator is attenuated to low photon numbers [3, 4]. This opens up optimization opportunities that are usually compromising the signal; because in this application the signal is attenuated anyway, signal attenuation in the modulator is irrelevant, as long as the power in between pulses is attenuated more. We propose a method to enhance the extinction ratio in QKD transmitter chips by adding a shorted saturable absorber (SA) behind the modulator. The SA's nonlinear nature reduces power between pulses more than during pulses, significantly boosting the extinction ratio with minimal added complexity.

In this work, we first look at the attenuation of different input powers in an SA in simulation and measurements. We then use these values to quantify the potential improvement of integrated QKD transmitter chips.

Saturable absorber simulation and measurement

An SA is saturated more by high input powers than by low input powers. When used correctly, this can reduce the power in between pulses more than during pulses, increasing the ratio between on and off states. In this section, we evaluate the attenuation levels of shorted SAs at different input powers and lengths through simulation and measurements.

Simulations were carried out in the time domain traveling wave (TDTW) software PICWave from PhotonDesign, using the SMART Photonics Gen 2 process design kit

(PDK) (version 1.0) [5]. The length of the SA was varied from 30 µm to 700 µm and the input power was varied from 10 dBm to -23 dBm at a wavelength of 1550 nm.
The simulated output powers for different input powers are shown in Fig. 1a. The black dashed line indicates no attenuation and the distance of the simulated output powers below the dashed line indicates the attenuation. Figure 1b shows this attenuation as a function of input power for different SA lengths. We can see a clear difference in attenuation for different input powers, which allows for optimization of the extinction ratio.

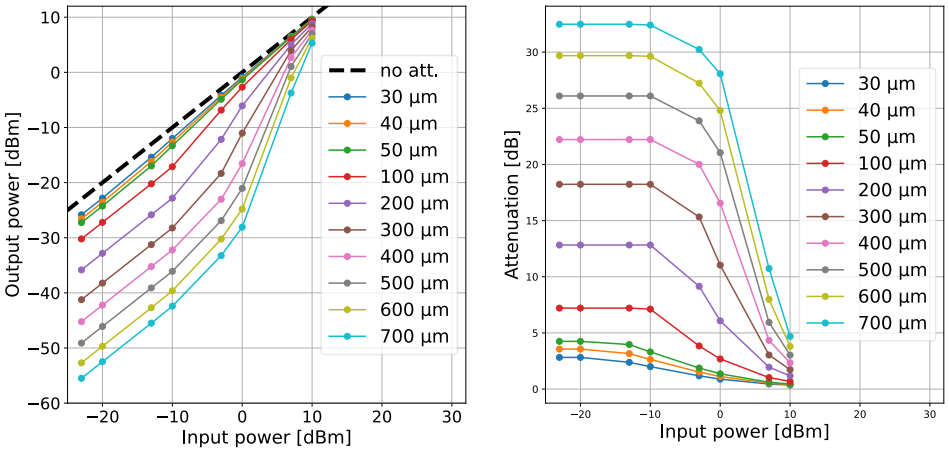

Fig. 1. Simulations in PICWave for SAs of different lengths and different input powers. a) Output power. b) Attenuation.

To confirm the results of the simulation, measurements on SAs fabricated in the generic InP platform of SMART Photonics [6] were carried out. The tested SA lengths vary from 30 µm to 400 µm. The SAs were probed with probe needles to short-circuit them and the light was coupled in and out of the chip using lensed fibres. Input powers between 5 dBm and -15 dBm were provided with an Agilent 81940A compact tuneable laser source. The output power was measured with an Agilent 81636B power sensor module. The input and output power is corrected for a coupling loss between the chip and lensed fiber of 4 dB per facet and losses in the passive waveguides of 3.2 dB/cm.

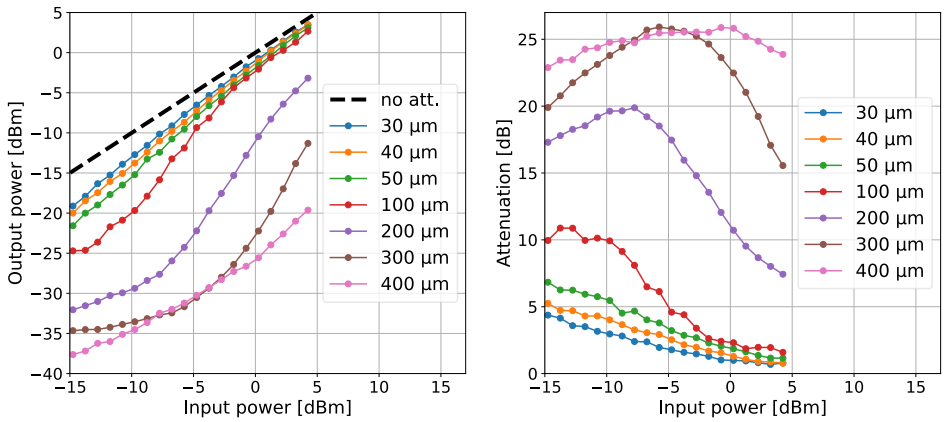

Fig. 2. Measurements on different length SAs on an InP chip produced in with SMART Photonics. a) Output power as a function of input power. b) Attenuation as a function of input power.

The measured output power for different input powers is shown in Fig. 2a. The black dashed line indicates no attenuation. The distance of the measurements below the dashed line indicates the attenuation. Figure 1b shows this attenuation as a function of input power for different SA lengths. The measurements confirm the expected effect: We see a clear difference in attenuation for different input powers, which allows for optimization of the extinction ratio.

QKD transmitter improvement

To see the effect of the shorted SAs on a transmitter, we used the QKD transmitter chip presented in [7]. Figure 3a shows a schematic overview of the transmitter, indicating also the proposed location of the shorted SA building block. To maximize the effectiveness of the SA, we determined the output power and extinction ratio after the original modulator. Then, with these values, we chose the SA length such that the difference in attenuation between on and off was as large as possible.

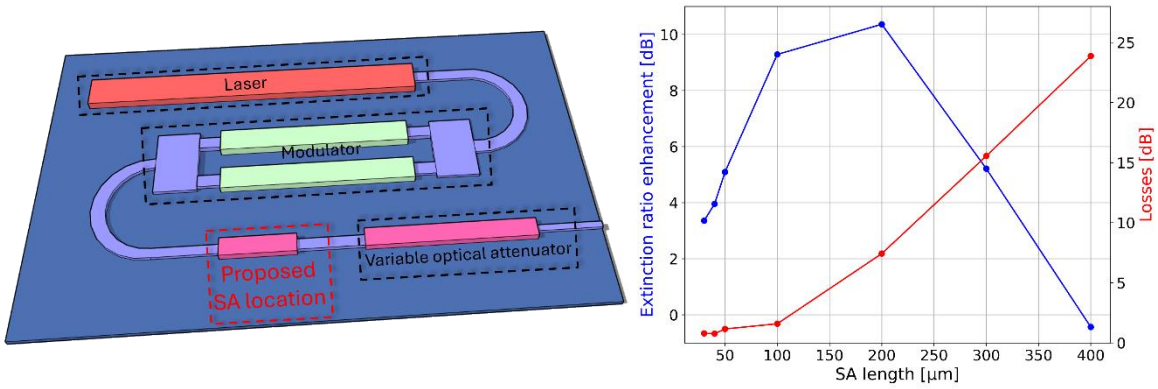

Fig. 3. a) Schematic overview of a QKD transmitter chip with the proposed location of the SA building block indicated in red.. b) Measurement results for extinction ratio enhancement and losses as a function of SA length for a modulator with an output power of 5 dBm and an extinction ratio of 19 dB.

For the design without the SA we find maximum powers of around 5 dBm and an extinction ratio of around 19 dB. At these input values the extinction ratio enhancement and losses for the different measured lengths are plotted in Fig. 3. As expected, the losses of the signal (right y-axis) go up for longer SA lengths, but this is not relevant because of the attenuation to low photon numbers afterwards. By adding a passive shorted SA of 200 µm behind the modulator, the extinction ratio would be increased from 19 dB to 29 dB, without compromising on the signal performance.

Discussion

Figure 2b shows a maximum for the attenuation curves, where it is not necessarily expected from simulations. This maximum comes from a noise floor in the experiments of around -35 dBm. Light attenuated to powers below -35 dBm is not reliably distinguished, limiting the measured attenuation to the difference between input power and the noise floor. From simulations we expect that an even larger improvement is

possible, but measurements with a lower noise floor need to be performed to confirm this. Longer SAs might not completely saturate, attenuating signal power more than wanted.

An important additional point to address for the measurements in this work, is that the experiments were done in steady state. Future work should also investigate the dynamic behaviour. Results from [8], indicate that the short carrier lifetimes in the quantum well SAs allow for modulation speeds well in the GHz range with this technique.

Conclusion

Adding an electrically shorted SA behind the modulator in a QKD transmitter chip can significantly enhance the extinction ratio, potentially reducing quantum bit error rates with minimal added complexity.

Because in QKD with attenuated lasers (both DV and CV QKD), the pulses are attenuated to low photon numbers before being sent out towards the receiver, the additional attenuation of the signal pulses by the SA, is irrelevant. Simulations and measurements confirm that the SA selectively attenuates power between pulses more than during pulses, allowing for an improvement in extinction ratio of up to 10 dB, from 19 dB to 29 dB.

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