Evaluation of Attenuation Methods for an Integrated, Weak Coherent Source for Quantum Key Distribution

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Quantum key distribution (QKD) systems that use weak coherent states often rely on attenuated lasers to generate signals with an average of less than one photon per pulse. Two ways of attenuating laser light in a weak, coherent, integrated QKD transmitter chip are compared in terms of noise, namely attenuation with Mach-Zehnder (MZ) interferometers and attenuation with semiconductor optical amplifiers (SOAs) biased as attenuators. Results from simulations and experiments on the optical spectrum of the output of the transmitter chip show that under reverse bias conditions the SOAs result in similar noise levels as the MZs. The footprint of the SOAs on the chip, however, is more than 50 times smaller than that of the MZs. This makes them the better candidate for the integrated, weak coherent QKD source.

Introduction

Quantum Key Distribution (QKD) allows the exchange of inherently secret cryptographic keys. Using quantum particles to exchange these keys, QKD schemes can guarantee key secrecy through the detectability of eavesdroppers, instead of assumptions on the computational power available to a potential, undetected eavesdropper [1], [2]. Most current QKD implementations rely on attenuated lasers to generate weak coherent states with an average of less than one photon per pulse [1]. QKD systems using different attenuation methods to achieve this have been demonstrated. To the authors' best knowledge, however, the influence of the different attenuation methods on the signal quality has not yet been investigated. This work aims to investigate the influence of two different on-chip attenuation methods on the noise in the signal of an integrated QKD transmitter chip [3], [4]. The two attenuation methods investigated are semiconductor optical amplifiers (SOAs) biased as absorbers and destructive interference after phase modulation in the arms of a Mach-Zehnder (MZ) interferometer. The goal is to compare the two methods for QKD in terms of noise.

The influence of the attenuation methods on the signal noise is investigated through the optical spectrum of the output of the QKD chip. The power at the signal wavelength and the level of the noise floor of the optical spectrum for different attenuation levels are compared for the different attenuation methods. The attenuation methods are first compared in simulations and then in measurements.

Simulations

Simulations are carried out in the time domain traveling wave (TDTW) simulation software PICWave from Photon Design [5] (version 6.1), using the SMART Photonics gen 2 process design kit (PDK) [6] (version 1.0). Light from an ideal, narrow linewidth laser at a wavelength of 1550 nm and a power of 0 dBm with no noise, is joined with the output of a SMART SOA, biased at 10 mA, to generate laser light with a spontaneous emission noise floor. This light is split and guided through a SMART SOA of 100 µm, a

SMART saturable absorber (SA) of 100 µm (necessary to simulate a reverse-biased SOA), and an MZ interferometer. The MZ interferometer is constructed using two lossless equal splitting ratio Y-junctions and SMART electro-optic phase modulators (EOPM) of 3040 µm in both arms.

The simulations run for different bias currents on the SOA, different bias voltages on the SA, and different bias voltages on one arm of the MZ interferometer while keeping the other arm biased at 0 V. The bias current on the SOA is swept from 15 mA to 0 mA. The voltage on the SA is swept from -0.1 V to -3 V. The voltage on the MZ arm is swept from -0.1 V to -3.5 V. The spectrum is obtained at each step. From these results, the peak and floor levels are obtained for comparison of the attenuation methods.

Simulation Results

The obtained spectra for MZ attenuation and SOA attenuation are shown in Fig. 1a. The simulated spectra show wavelength and bias-dependent noise figures as characterized in [6]. From these spectra, the peak and floor levels are determined. Peak levels for different bias levels are taken from the spectrum at 1550 nm. Floor levels for different attenuation bias levels are determined by averaging over the values of the spectrum between 1549 nm and 1549.5 nm and between 1550.5 nm and 1551 nm. The floor levels as a function of the signal levels for the two attenuation methods are shown in Fig. 1b. The MZ interferometer shows a linear relation between the floor and peak levels. The SOA, when positively biased, shows floor levels that are approximately 3 dB higher than for the MZ interferometer, indicating worse performance in terms of noise. When reverse-biased, the floor levels change to similar levels as for the MZ interferometer, indicating equal performance. For QKD transmission, attenuation in the order of -60 dB is necessary [3], warranting reverse bias on the SOA and therefore rendering the performance of the SOA equal to the MZ in terms of noise measured in this experiment.

Measurements

Measurements on the optical spectrum of the QKD transmitter chip are carried out using an optical setup with a bare chip. The chip used for measurements is produced by SMART

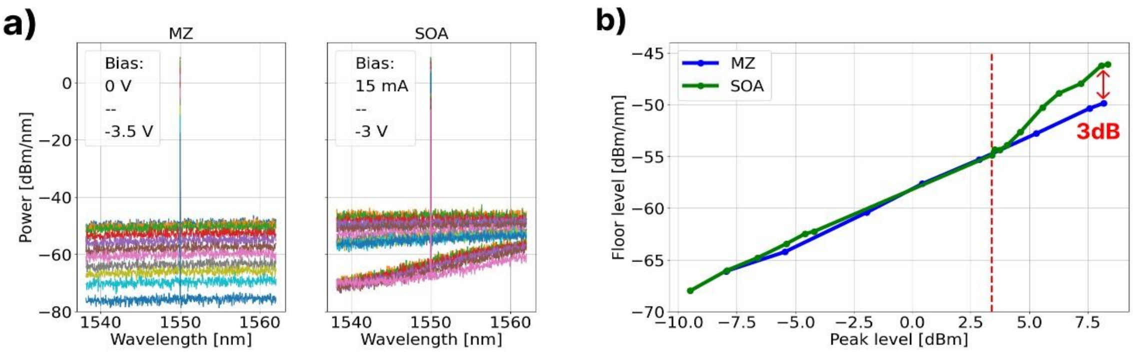

Figure 1. a) Simulated spectra for different attenuation methods. MZ (left), SOA (right). b) Simulated optical spectrum noise floor power as a function of the power at the signal wavelength for SOA and MZ attenuators. The signal powers are taken at 1550 nm, the noise floor powers are averaged values from between 1549 nm and 1549.5 nm and between 1550.5 nm and 1551 nm. The transition from positive bias to reverse bias for the SOAs is indicated in red.

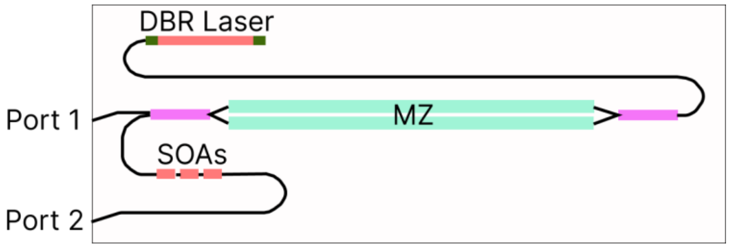

Figure 2. Simplified overview of the chip used for measurements. Light from a DBR laser is guided towards an MZ modulator that can guide the light either towards Port 1 or towards an SOA section containing three SOAs. From the SOAs the light is guided towards Port 2.

Photonics on a multi-project wafer run (SP27). An overview of the chip is shown in Fig. 2 and the chip is described in more detail in [3]. Light from a distributed Bragg reflector (DBR) laser with a gain section of 500 µm is guided through a waveguide to an MZ interferometer containing EOPMs of 3040 µm long. At the output of the MZ, light is guided either towards an output at the facet of the chip (Port 1) or towards a waveguide containing three 100-µm-long SOAs. After the three SOAs, the light is guided toward the second output of the chip (Port 2). The elements on the chip are contacted using probe needles on gold pads. The voltage and current supplies used are Keithley Model 2400 source meters and a Thorlabs Pro8000 Current module LDC80xx. The output light is coupled to a lensed single-mode fiber placed on a Thorlabs BPC203 piezo-controlled fiber stage.

To measure the spectra for different attenuations with the MZ as an attenuator, Port 1 is connected to an OSA (Yokogawa AQ6375). The laser bias is kept constant at 95 mA and the bias voltage on one arm of the MZ is swept from maximum output (-3.7 V) to minimum output (-6.7 V). At every step of the sweep, the optical spectrum is acquired. To measure the spectra for different attenuations using the SOAs, the output from Port 2 is connected to the OSA. The MZ is biased at a constant bias value for maximum input into the SOAs (-6.7 V). The SOA bias is swept from the transparency current (set to equal the maximum output at Port 1, measured at 29.4 mA) to 0 mA and from -0.1 V to -8.5 V. At each step of the sweep, the optical spectrum is acquired. The spectrum is measured on a range of 20 nm around a center wavelength of 1550 nm, taking 1001 points with a resolution of 2 nm. The relatively wide resolution is necessary to reach the sensitivity needed to measure noise down to levels in the order of -80 dBm/nm.

As an additional attenuation method, the coupling efficiency between the chip facet and the lensed fiber is reduced to attenuate the light coupled into the single-mode fiber. The laser is biased at a constant current of 95 mA and the MZ is biased for maximum output power at Port 1 (-3.7 V). The lensed fiber is slowly retracted to decrease the coupling efficiency, in steps of 1 µm, for a total of 40 µm. After each retraction, the optical spectrum is acquired.

Measurement Results

The measured spectra for MZ attenuation, attenuation with SOAs, and attenuation by retracting the lensed fiber are shown in Fig. 2a from left to right respectively. The peak levels are determined from these optical spectra by taking the value measured at 1550 nm. The noise floor levels are determined from the optical spectra by taking the value measured at 1544 nm. The noise floor levels as a function of the peak levels for the three attenuation methods are shown in Fig. 2b. The measurement results of the MZ interferometer as attenuator and the attenuation by retraction of the lensed fiber are very similar. The peak level and the noise floor level show a linear relation. The attenuation with SOAs shows

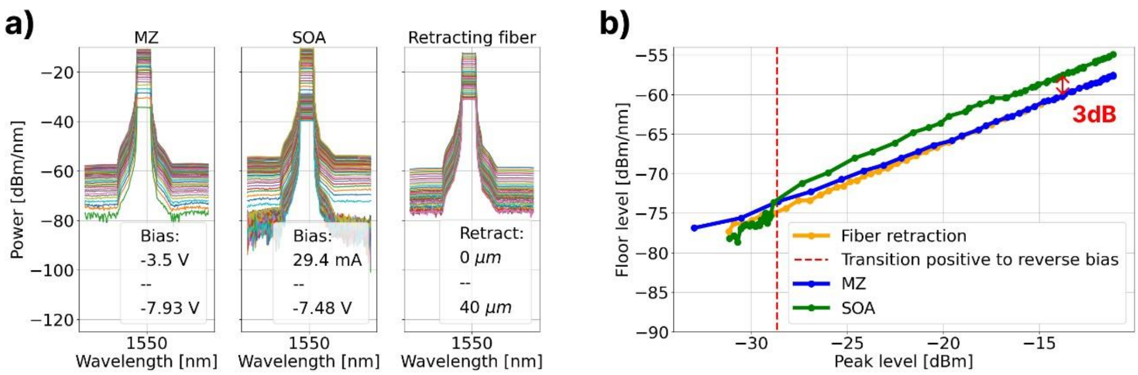

Figure 3. a) Measured optical spectra for different attenuation levels with different attenuation methods. The spectra are obtained on a range of 20 nm around a center wavelength of 1550 nm, taking 1001 points with a resolution of 2 nm. From left to right: SOAs, MZ, fiber retraction. b) Measured optical spectrum noise floor levels as a function of the levels at signal wavelength for SOAs, MZ, and fiber retraction. The signal powers are measured at 1550 nm and the noise floor values are measured at 1544 nm. The transition from positive bias to reverse bias for the SOAs is indicated in red.

similar behavior as found in the simulations. For positively biased SOAs, the noise floor levels are approximately 3 dB higher than for the other two attenuation methods. When reverse-biased, the noise floor levels drop to similar levels as for the other two attenuation methods. This confirms the finding from the simulations that for reverse bias, the SOAs show similar performance to the MZ attenuators. A possible explanation for the higher noise of the SOAs as attenuators at positive bias is that additional spontaneous emission is caused by the excess carriers in the SOAs as a result of the forward bias.

Conclusion

By comparing the power at signal wavelength to the power level of the noise floor of the optical spectrum, two different on-chip attenuation methods for an integrated weak coherent QKD transmitter are compared. Simulations and measurements show that for reverse bias, SOA attenuators show similar performance as MZ attenuators. To reach attenuation levels needed for QKD, the SOA attenuators will be reverse-biased. This is encouraging for the use of SOAs as attenuators in the QKD chip, since the footprint of the SOA attenuators is more than 50 times smaller than that of the MZ interferometers, making them the better candidate.

References

[1] H. Lo, M. Curty, and K. Tamaki, "Secure Quantum Key distribution," Nature Photonics, vol. 8, 595604, 2014.

[2] S. Pirandola, et al., "Advances in quantum cryptography," Adv. Opt. Photon., vol. 12, 1012-1236, 2020.

[3] H.O. Çirkinoglu, R. Santos, K. Williams and X. Leijtens "Monolithically integrated differential phase shift transmitter for quantum key distribution," in Proceedings of the 22nd European Conference on Integrated Optics, 2020.

[4] M. Smit, et al., "An introduction to InP-based generic integration technology," Semiconductor Science and Technology, vol. 29, 083001, 2014.

[5] Photon Design, PICWave, [Online]. Available: *https://www.photond.com/products/picwave.htm*

[6] PICWave SMART Photonics Gen2 PDK [Online]. Available: https://*www.photond.com/products/picwave/picwave_features_09_3.htm*