

Fast optical source for quantum key distribution based on semiconductor optical amplifiers

M. Jofre^{1,*}, A. Gardelein¹, W. Amaya², J. Capmany², R. Ursin^{3,4}, L. Peñate⁵, D. Lopez⁵, J. L. San Juan⁶, J. A. Carrasco⁷, F. Garcia⁷, J. Torcal⁸, L. M. Sanchez-Brea⁸, E. Bernabeu⁸, J. M. Perdigues⁹, T. Jennewein¹⁰, G. Anzolin¹, J. P. Torres^{1,11}, M. W. Mitchell¹, V. Pruneri^{1,12}

¹*ICFO-Institut de Ciències Fòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain*

²*Institute of Telecommunications and Multimedia Applications (ITEAM), Universidad Politècnica de Valencia, Spain*

³*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Austria*

⁴*Faculty of Physics, University of Vienna, Austria*

⁵*ALTER Technology Group, Spain*

⁶*LIDAX, 28850 Torrejón de Ardoz, Spain*

⁷*EMXYS, 03206 Elche, Spain*

⁸*Departamento de Óptica, Universidad Complutense de Madrid, 18040 Madrid, Spain*

⁹*European Space Agency, Noordwijk, The Netherlands*

¹⁰*Institute for Quantum Computing, University of Waterloo, Canada*

¹¹*Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, Spain*

¹²*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain*

marc.jofre@icfo.es

Abstract: A novel integrated optical source capable of emitting faint pulses with different polarization states and with different intensity levels at 100 MHz has been developed. The source relies on a single laser diode followed by four semiconductor amplifiers and thin film polarizers, connected through a fiber network. The use of a single laser ensures high level indistinguishability in time and spectrum of the pulses with the four different polarizations and three different levels of intensity. The applicability of the source is demonstrated in the lab through a free space quantum key distribution experiment which makes use of the decoy state protocol. A lower bound secure key rate of the order of 1.82 Mbps and a quantum bit error ratio as low as 1.14×10^{-2} and 93 bps for an equivalent attenuation of 35 dB were achieved. To our knowledge, this is the fastest polarization encoded QKD system which has been reported so far. The performance, reduced size, low power consumption and the fact that the components used can be space qualified make the source particularly suitable for secure satellite communication.

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1. Introduction

Quantum key Distribution (QKD), guarantees absolutely secure key distribution, since making use of the principles of quantum physics [1], using the fact that it is not possible to measure or copy an unknown quantum state without being detected [2]. A cryptographic key is generated out from the measurement of the information encoded into specific quantum states of a photon (e.g. polarization or phase). The first QKD scheme, proposed by Bennett and Brassard [3], employed single photons sent through a quantum channel, plus classical communications over a public channel to generate a secure shared key. This scheme is commonly known as the BB84 protocol. Attenuated laser pulses or *faint pulse sources* (FPS), which in average emit less than one photon per pulse, are often used as signals in practical QKD devices. With the introduction of the decoy state protocol [4], faint pulse systems can offer comparable QKD security with respect to single photon sources, in particular for high loss situations [5].

Current photon-detector technology and optical guiding media losses limit QKD on Earth to 200 km in optical fibers [6] and 144 km in free-space links [7]. The unique features of space can potentially offer extremely long propagation paths, essential for the realization of a global QKD network [8, 9]. Nevertheless, many components of the system, besides the source, require special attention for the implementation of QKD. The development of a source suitable for space, apart from the optical design, requires a demanding optomechanical engineering as well as high level of integration with the electronics.

In this paper, we report the development of a novel, compact and reliable FPS-based *semiconductor optical amplifiers* (SOAs) which emits pulses at a repetition rate of 100 MHz, suitable for free-space QKD applications. It has been measured that the source achieves a Lower Bound

Secure Key Rate of 1.82 Mbps implementing the BB84+decoy state protocol. The source is capable of generating pulses at least three different intensity levels (i.e. number of photons per pulse) and four different polarization states. The demonstrated FPS ensures high level of indistinguishability among the different intensity and polarization pulses and ensures phase incoherence of consecutive generated states. It is based on a single diode emitting a continuous optical train of pulses externally modulated in intensity and polarization by using a combination of four SOAs and polarizing optical elements. The wavelength, reduced power consumption, compactness and space qualifiable optoelectronic components constituting the source make it very suitable for space-based QKD transmission. Although the proposed source has been conceived for free space QKD at around 850 nm, the concept can be extended to other wavelengths (e.g. 1550 nm) and other media, including optical fibers.

2. The compact faint pulse source

In order to use it for space applications, the proposed integrated FPS source consists of space-qualified discrete components (Figure 1): a single semiconductor laser diode emits a continuous train of optical pulses at 100 MHz, equally split to four outputs using three in-fiber single-mode 1x2 couplers. Each fiber output is followed by an integrated (waveguide) SOA. The four bare fibers to the coupling tube are accurately positioned on a custom opto-mechanical mount to simultaneously achieve the correct launching to the polarizers substrate sheet as well as to introduce a desired 70 dB coupling-loss to work in the single-photon regime at the end of the output bare fiber. Each polarizer is accurately oriented to produce one of the four polarizations (0° , 90° , 45° and -45°) required for BB84 protocol. Finally, the output fiber can be connected to the corresponding optical link interface (e.g. a telescope for free-space communication or optical fiber for terrestrial links).

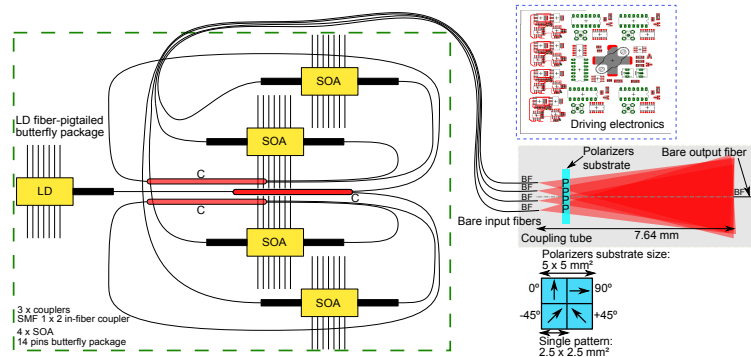


Fig. 1. Schematic of the QKD source. [LD] denotes a laser diode, [C] a single-mode in-fiber 1x2 coupler, [SOA] a semiconductor optical amplifier, [P] a free-space thin-film polarizer and [BF] a single-mode bare fiber.

The *distributed feedback* (DFB) laser diode (LD) source is directly modulated at 100 MHz by a train of electrical pulses of about 1 ns duration. The generated optical pulses do not have any phase coherence among them due to the fact that the laser is set below and above threshold from one pulse to the subsequent one, thus producing a random phase for each pulse [10]. In this way phase coherence of consecutive generated states is absent, which otherwise would be detrimental for the link security. Single-mode 1x2 in-fiber couplers perform the task of passively splitting the continuous optical pulse train into four equal outputs, while sufficiently preserving the polarization state linearity generated by the LD, before entering the SOAs.

For the implementation of a QKD system using decoy state protocol, besides four different

polarization states (0° , 90° , 45° and -45°), the FPS source should generate three intensity levels (optimally $1/2$, $1/8$ and 0 photons in average per pulse [11]) in order to operate in the single photon regime while optimizing the decoy state protocol. Each SOA performs the double task of spatial switching and amplitude modulation; it selects a specific fiber output while, by changing the driving voltage, it generates the three intensity levels needed for the decoy state protocol. Note that the spatial switching among the four fiber outputs is then transformed in polarization modulation according to the scheme described above. In this way intensity and polarization modulation can be achieved with high extinction ratio. Note that the common parameter of interest for a SOA is the gain. However in this case the frequency response to an electrical signal is equally important, in particular for the time and spectral indistinguishability of the pulses with different polarizations and energy levels.

3. Experimental measurements

Figure 2 shows the train of optical pulses generated by the laser diode when driven by electrical pulses of 1 ns at 100 MHz. The resulting optical pulse duration is about 400 ps. Since all optical pulses are generated in the same way, by direct modulation of the laser diode, they can be assumed to be indistinguishable. Furthermore, the short optical pulse duration of 400 ps (small duty cycle) has the advantage of increasing the signal-to-noise ratio, since the measurement window (detection time) in the receiver side can be reduced.

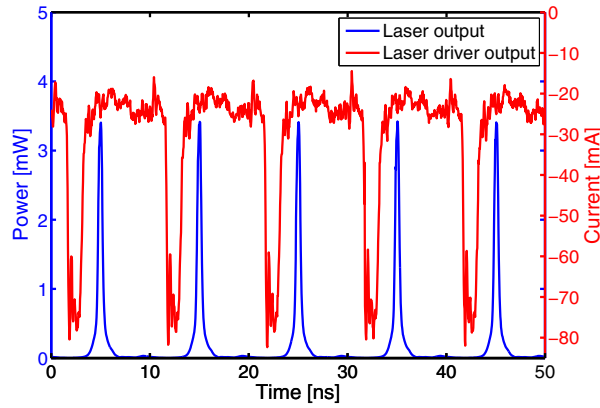


Fig. 2. Optical pulse train generation. Laser driver output (upper curve, right axis) produces few-ns, negative-going pulses which drive the DFB laser briefly above threshold. The laser output (lower curve, left axis), shows pulses with 100 MHz repetition rate and sub-ns duration.

In Figure 3, the pulses with different intensities required to implement the decoy state protocol are shown for all the four SOAs, together with the driving signals, loaded with a 50Ω resistance for monitoring purposes. Notice that the modulation time window of the driving signals is much larger (> 5 ns) than the optical pulse thus minimum distortion is produced. A continuous periodic sequence, driving the four SOAs at the same time, is used to set the intensity level of a single SOA while the other three SOAs remaining in the OFF state. In particular, the three intensity levels correspond to: a high intensity level state which is set to $1/2$ average photon per pulse by adjusting the coupling efficiency to the output bare fiber; then a second lower intensity level and the third level is set as vacuum (the SOA is not switched ON).

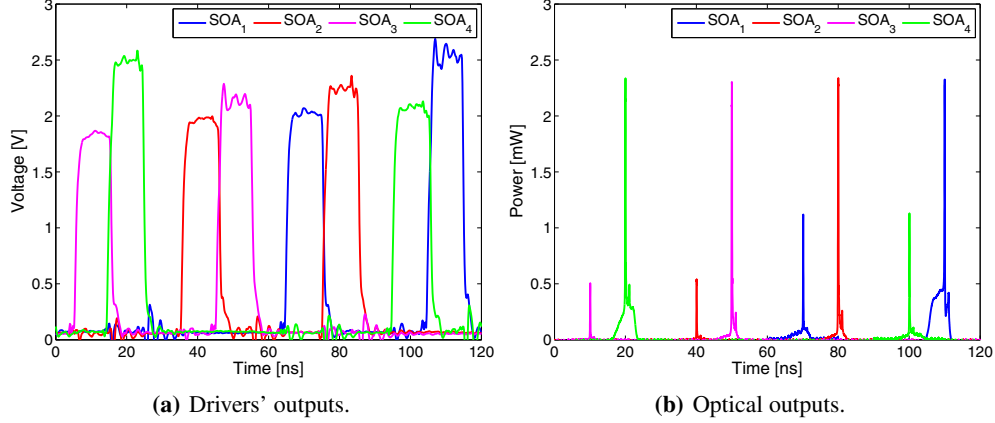


Fig. 3. Driving signals to the four SOAs (a) and corresponding generated optical pulses (b), as required for the implementation of the BB84+decoy states protocol. Note that the driving voltages are such that the peak optical intensities from the four SOAs are similar.

4. QKD free-space transmission

Figure 4 shows the setup used for the BB84+decoy state transmission measurement. The output bare fiber was connected to a free-space collimator pointing to the polarization-sensitive detection module, a.k.a. “Bob module” commonly used for polarization-encoded QKD. Alice and Bob time references were synchronized using a classical channel providing a 10 MHz clock signal. The detections from the *single-photon detectors* (SAPD) were recorded by a timetagging unit and then transferred to a computer to derive the relevant parameters (e.g. *Lower Bound Secure Key Rate* (LBSKR), *Raw Key Rate* (RKR) and *Quantum Bit Error Ratio* (QBER)). The timetagging unit allows 10 Mcps transmission to the computer, by *direct memory access* (DMA), and also it has a timestamp resolution of 78.125 ps. To account for 500 ps jitter of SAPD (Perkin Elmer SPCM-AQ4C) a 5 ns time window was implemented by software, allowing to reduce the background noise.

The free-space link was emulated in the laboratory by placing different neutral density attenuators along the propagation path from Alice (the source) to Bob (the receiver). We then measured the rates and performances of the QKD BB84+decoy state protocol using the presented source. In the implementation of the BB84 protocol, only single-photon pulses contribute to the secure key, while in the 3-state decoy state protocol the full range of intensities should be considered.

All but privacy amplification was implemented, were the lower bound for the secure key generation rate can be obtained as

$$R \geq q \frac{N_\mu}{t} \{-Q_\mu f(E_\mu) H_2(E_\mu) + Q_1 [1 - H_2(e_1)]\} \quad (1)$$

where q depends on the implementation (1/2 for the BB84 protocol), N_μ is the total number of signal pulses sent, t is the time duration of the QKD transmission, μ represents the intensity of the signal states, Q_μ is the gain of the signal states, E_μ is the signal pulses QBER, $f(x)$ is the bi-direction error correction efficiency (taken as 1.16 [12], for an error ratio of 1%) and $H_2(x)$ is the binary Shannon information function, given by

$$H_2(x) = -x \log_2(x) - (1-x) \log_2(1-x) \quad (2)$$

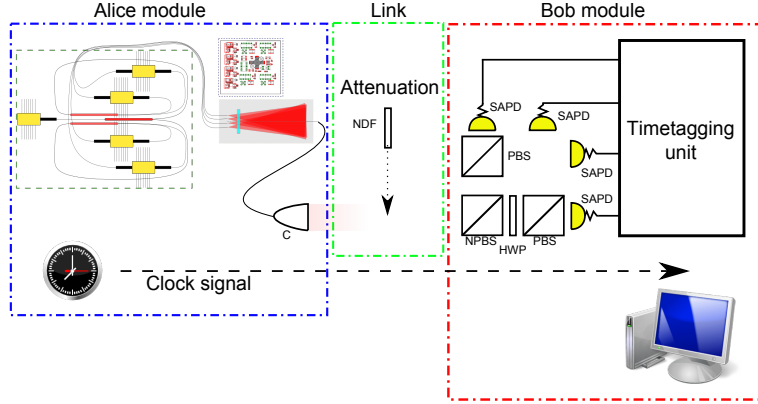


Fig. 4. Schematic of the QKD measurement setup. Alice module is composed of the FPS also providing a common clock signal of 10 MHz in order to synchronize Alice and Bob modules. [C] denotes a fiber to free-space collimator, [NDF] a neutral density filter, [NPBS] a non-polarizing beamsplitter, [HWP] a half-wave plate, [PBS] a polarizing beamsplitter and [SAPD] a single-photon detector.

5. Results and discussion

Figure 3 shows the SOAs' capability to be driven at 100 MHz while achieving spatial switching operation and intensity level generation, suitable for BB84+decoy state protocol. In addition low driving voltages are needed, making the design suitable for electronic integration with low electrical power consumption drivers. Furthermore, by design, the phase of each pulse varies at random between pulses due to the fact that, as it was already mentioned, pulses are generated by taking continuously the laser diode above and below threshold, as explained in [10]. It is clear that the optical pulses from the SOAs have *Amplified Spontaneous Emission* (ASE) noise reducing the indistinguishability of the different states, this can be mitigated by using proper filters and/or selection of SOAs. In fact, SOAs 2 and 3 produce nearly identical pulses without the use of any filter.

Figure 5 shows the detected RKR and QBER, and the resulting LBSKR, for different link attenuations. In the transmission measurement the detectors' efficiency was set to 50%, 2 dB were accounted for losses due to the transmitting and receiving optical setup with a background yield of 5.58×10^{-4} . As expected, for signal rates well above the noise floor the RKR decreases exponentially as the attenuation increases, so does the LBSKR. When the signal rate decreases the noise starts to dominate, so the QBER increases rapidly as well as the LBSKR, until the QBER is > 0.11 when the LBSKR drops completely to zero. In particular, results for the emulated BB84+decoy state protocol transmission, for a particular attenuation of 6 dB, are shown in Table 1. We have achieved a LBSKR of 1.82 Mbps with a QBER as low as 1.14×10^{-2} for an attenuation of 6 dB while the achieved LBSKR became 93 bps for an attenuation as high as 35 dB.

6. Conclusions

We have shown that a single photon source based on an attenuated laser diode for QKD applications can be built based on a novel scheme including semiconductor optical amplifiers. The source is capable of generating pulses of random polarization distributed over four states and three intensity levels required for BB84+decoy state protocol. A lower bound secure key rate of 1.82 Mbps with a quantum bit error ratio as low as 1.14×10^{-2} for an attenuation of 6 dB. To

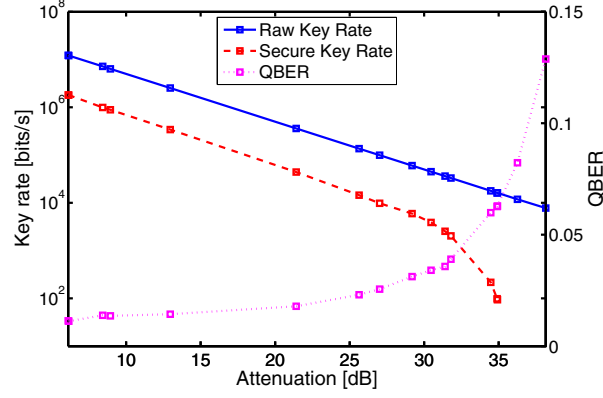


Fig. 5. QKD BB84 implementing decoy states transmission results. Raw Key Rate (blue solid line), Lower Bound Secure Key Rate (red dashed line) and QBER (magenta dotted line). The detectors' efficiency was set to 50%, 2 dB were accounted for losses due to the transmitting and receiving optical systems and background yield 5.58×10^{-4} .

Table 1. Summary of the QKD results for a BB84 transmission, implementing the decoy state protocol. The obtained values are for a 6 dB attenuation, where μ , v_1 and v_2 are the signal, decoy 1 and decoy 2 (ideally vacuum) states. The computed values are the gains for the signal Q_μ , decoy 1 Q_{v_1} , decoy 2 Q_{v_2} states and the QBER for the signal states e_μ . Finally the lower bound of the secure key rate R_{secure} , for the presented source, is 1.82 Mbps with a QBER as low as 1.14×10^{-2} while a R_{secure} of 93 bps for an attenuation as high as 35 dB.

Parameter	Value	Parameter	Value
Attenuation	6 dB	Q_μ	1.18×10^{-1}
μ	0.5	Q_{v_1}	1.8×10^{-2}
v_1	6.6×10^{-2}	Q_{v_2}	3×10^{-3}
v_2	2×10^{-3}	e_μ	1.14×10^{-2}
R_{secure}	1.82 Mbps	$f(E_\mu)$	1.16

our knowledge, this is the fastest polarization encoded QKD system which has been reported so far. Given the relatively low driving voltages of the SOAs, the laser diode and the other integrated optical components, the proposed transmitter is potentially low power consumption, highly integrable and stable. The experimental demonstration has been carried out at 850 nm, for the implementation in free-space links, with 100 MHz generation rates. However, taking into consideration that the SOA's bandwidth can go well beyond 10 GHz and operate also at other wavelengths (e.g. 1310 nm and 1550 nm for fiber transmission), the source can be easily scalable to higher bit rates, the upper limit probably being set by the laser diode itself.

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