QUBE – Towards Quantum Key Distribution with Small Satellites

Lukas Knips[1,2,3], Michael Auer[1,3], Adomas Baliuka[1,3], Ömer Bayraktar[4,5], Peter Freiwang[1,3], Matthias Grünefeld[6], Roland Haber[7], Norbert Lemke[6], Christoph Marquardt[4,5], Florian Moll[8], Jonas Pudelko[4,5], Benjamin Rödiger[8], Klaus Schilling[7], Christopher Schmidt[8], Harald Weinfurter[1,2,3]

[1] *Ludwig Maximilian University (LMU), Schellingstr. 4, D-80799 Munich, Germany,*
[2] *Max Planck Institute of Quantum Optics (MPQ), Hans-Kopfermann-Str. 1, D-85748 Garching, Germany,*
[3] *Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 Munich, Germany,*
[4] *Max Planck Institute for the Science of Light (MPL), Staudtstr. 2, D-91058 Erlangen, Germany,*
[5] *Friedrich Alexander University of Erlangen-Nürnberg (FAU), Staudtstr. 7/B2, 91058 Erlangen,*
[6] *OHB System AG, Manfred-Fuchs-Straße 1, D-82234 Weßling, Germany.*
[7] *Center for Telematics (ZfT), Magdalene-Schoch-Straße 5, D-97074 Würzburg, Germany,*
[8] *German Aerospace Center (DLR) IKN, Münchener Str. 20, D-82234 Weßling, Germany*

lukas.knips@mpq.mpg.de

Abstract: Quantum Key Distribution (QKD) in space will be integral for future quan-tum networks. The space mission QUBE will test novel integrated optics components in a three-unit CubeSat demonstrating an economic route for global-scale QKD. © 2022 The Author(s)

Quantum Key Distribution (QKD) is a provably secure method for distributing secret keys between two trusted parties over a quantum channel. Depending on the use case, this channel can either be an optical fiber or a free-space channel, both associated with a very different scaling of the loss depending on the link distance. While fiber-based systems with exponential damping of the signal are surely beneficial in metropolitan areas, free-space systems are suffering from only quadratic losses due to expanding beams. Hence, as demonstrated by the MICIUS mission [1], exchange of a key is possible between a satellite and an optical ground stations (OGS), thereby indeed enabling QKD on a global scale [2]. While this large mission demonstrated its feasibility, the QUBE missions are focussing on a more economic solution for global key exchange. Small satellites (cube satellites assembled in multiples of $10 \times 10 \times 10\,\mathrm{cm}^3$ cubes) are currently revolutionizing numerous applications in space like earth observations or ubiquitous internet connection. Provided QKD payloads can operate with a small size, weight and power (SWaP) profile, also secure key exchange can benefit from this game-changing technology.

The space mission QUBE targets to test two different, highly integrated QKD sender modules together with an integrated quantum random number generator (QRNG) in a three-unit CubeSat. It is planned that QKD signals will be exchanged between the satellite at a low earth orbit (LEO) at about 500 km above earth with the OGS located at the DLR in Oberpfaffenhofen, Germany. The two quantum payloads and an optical terminal (aperture 20 mm) will occupy approximately one unit in volume, with the remaining two liters required for system operation including power supplies, reaction wheels and a star tracker.

The two quantum payloads are assembled together with control electronics on two printed circuit boards with a size of $9 \times 9\,\mathrm{cm}^2$ each and have a combined height of less than 4 cm. One of those is featuring a discrete-variable BB84 polarization-encoding system running at a repetition rate of 100 MHz based on micro-optics assembling [3] (see Fig. 1 (a)). Faint laser pulses from four vertical-cavity surface-emitting lasers (VCSELs) emitting at approximately 850 nm are polarized using an array of precisely cut and assembled stripes of synthetic foil polarizers. An array of microlenses couples the light into a waveguide chip to spatially overlap the four input modes in an outgoing single-mode fiber. The second quantum payload is a system comprised of a QRNG (see Fig. 1 (b)) and an optical source for quadrature-modulated weak-coherent states, both integrated on two separate Indium-phosphide photonic integrated circuits on areas on the order of $10\,\mathrm{mm}^2$. The QRNG is based on optical homodyne measurements of the vacuum state [4]. The QKD source is able to run either time-bin BB84 or continuous-variable protocols at a wavelength tunable between about 1569 nm and 1571 nm using a DBR laser modulated by nested Mach-Zehnder interferometers and then coupled into a single-mode fiber. Besides compactness both integrated systems warrant high (thermo-)mechanical robustness of the optical system crucial for reliable operation in space. The QKD units minimize the SWaP to an overall volume of $1/3\,\mathrm{U}$, a total weight of below 150 g and a power consumption of below 2 W and 5 W, respectively.

Optical communication as well as the free-space quantum channel between the satellite and the ground station are provided by the laser communication terminal OSIRIS. Its laser (100 mW, 1550 nm) is used for tracking as well as for synchronizing satellite and OGS. The three optical signals are combined using an optical triplexer before

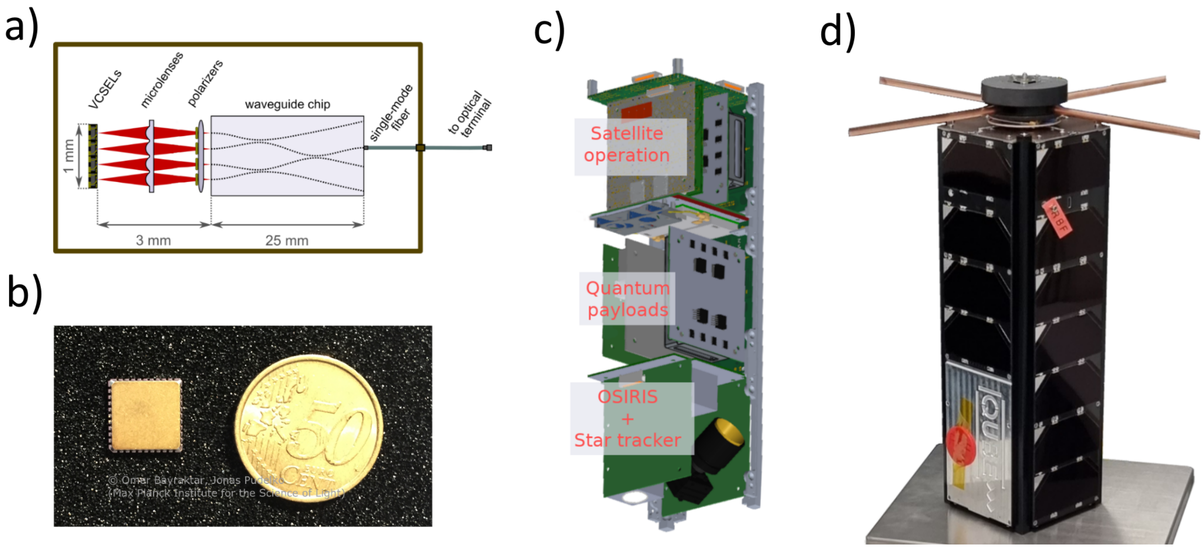

Fig. 1. (a) Scheme of the polarization-encoding source using micro-integrated optics: The polarized optical pulses of four vertical-cavity surface-emitting lasers (VCSELs) are focussed into a waveguide chip to overlap the four spatial modes in a single-mode fiber for transferring the QKD signals to OSIRIS. (b) Indium-Phosphite-based Photonic Integrated Circuit (PIC) for quantum random number generation inside a hermetically sealed ceramic package next to a 50 Cent coin. Another InP-based PIC as QKD sender is also connected to OSIRIS. (c) Rendering of the interior of the CubeSat showing the main modules for the satellite operation (e.g., power supplies, attitude control, UHF communication, on-board computer), the quantum payloads, the optical terminal OSIRIS and the star tracker. (d) Photo of the integrated 3U satellite QUBE (height: 30 cm).

being fed into the communication terminal optics. All subsystems are electrically connected over the CubeSat bus standard UNISEC encompassing the power supply as well as various communication and data lines. Telemetry and telecommand is performed via UHF (9.6 kbit/s up- and downlink), which also facilitates software updates and post processing tasks.

A multitude of experiments is planed, ranging from simple on-board performance evaluation without downlink over link characterization measurements to complex sequences where QRNs are generated and sent via one of the two QKD modules. For a sun-synchronous orbit, we expect one to two overflights per night with a link duration of about four to seven minutes each. During overflight, the satellite orientation has to be pre-stabilized within $\pm 1^\circ$ towards the OGS by three reaction wheels, enabling OSIRIS to start the active beam tracking and finally one of the QKD payloads to transmit quantum signals.

All satellite components have been tested on sub-system level regarding their robustness against vibrational loads and thermal cycles in vacuum. Resilience against radiation was evaluated by irradiating the optical components with protons and the entire sub systems with gamma radiation (Cobalt-60 source) with a total ionizing dose of 25 krad corresponding to a mission duration of about 2 years. After passing all tests, the satellite was fully assembled (Fig. 1(d)) and is currently tested on satellite-level before integrated into a CubeSat deployer. Characterization measurements of the QKD modules show that a source-intrisic QBER as low as 1.7% can be reached (including the triplexer and the optics of the optical terminal). The launch of the satellite is planned for late 2022.

Given the small aperture of OSIRIS and an expected link loss of about 50 dB to 60 dB, this mission will not yet demonstrate secure key exchange. However, operating the QKD payloads with a few photons per pulse, this first QUBE satellite will enable full evaluation of both platforms to demonstrate the feasibility of QKD on such small satellites for cost-efficient and secure global communication.

Acknowledgments.—We acknowledge funding by BMBF (project QUBE) and from DFG under Germany's Excellence Strategy - EXC-2111 - 390814868.

References

1. S.-K. Liao et al., Nature **549**, 43 (2017)
2. S.-K. Liao et al., Phys. Rev. Lett. **120**, 30501 (2018).
3. G. Vest et al., IEEE JSTQE **21**, 3 (2014).
4. C. Gabriel et al., Nature Photonics **4**, 711 (2010).

138.246.3.246 {ts '2022-08-11 05:48:11'}