# A modulator-free QKD transmitter

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Quantum key distribution (QKD) [1] is a powerful method for guaranteeing the confidentiality of future communication networks. It has progressed from laboratories to real-world implementations and is gradually being integrated into existing optical networks [2]. However, its commercial success still requires significant innovations that will make the technology more robust and affordable. As a step towards this goal, we propose and demonstrate a novel light source that can generate pulses modulated in phase without the aid of an external phase modulator. This allows to considerably reduce the source driving voltage and to reliably control the phase randomisation of the emitted pulses. By changing the electrical signals only, a diverse range of QKD protocols can easily be accommodated. This development makes QKD devices substantially more compact, versatile and energy-efficient, features that are essential for widespread adoption.

Our scheme solves three challenging problems. Firstly it enables the first example of sub-volt halfwave phase modulation. Compatible with CMOS driving, it removes the need for high speed electrical amplifiers that would otherwise add to the system cost and complexity. Secondly it simplifies the QKD optics by eliminating the external phase modulator and other free space or fibre optic components. Finally it allows QKD protocols as different as the BB84 and the DPS to coexist in the same optics platform, which will facilitate and promote interoperability of QKD protocols in the same network.

Figure 1(a) shows a schematic of our phase-modulated light source, consisting of a pair of laser diodes connected via an optical circulator and driven from specific electrical patterns. The ‘phase preparation’ laser is directly modulated to produce a train of pulses of nanosecond duration from quasi steady-state emissions. Each of these long pulses coherently seeds a block of two (or more) secondary, short optical pulses (<100 ps) of the ‘pulse generation’ laser. The relative phase of these secondary pulses can be set to an arbitrary value by directly modulating the driving voltage applied to the phase preparation laser, while their intensity and frequency are essentially unaffected.

Figure 1(b) plots the measured phase shift of subsequent laser pulses as a function of the modulation voltage applied to the phase preparation laser. The phase shift can be either positive or negative, and is approximately linear with the signal amplitude. We determine its halfwave voltage $V_\pi$ as 0.35 V. This value is approximately 10 times lower than for conventional phase modulators based on $LiNbO_3$ crystals or semiconductor waveguides. It is also the first example of a sub-volt phase modulation for any modulation method. We ascribe this low $V_\pi$ to the cavity enhancement of the electro-optic effect in the phase preparation laser. As $V_\pi$ is sufficiently low to be driven directly by CMOS logic, we expect this breakthrough will significantly reduce the complexity, as well as energy and physical footprint, of a QKD transmitter.

We now demonstrate the suitability of the source for QKD applications. The source is biased to transmit phase encoded light pulses at a clock rate of 2 GHz, leading to effective QKD clock rates of 1 and 2 GHz for the BB84 and DPS protocols, respectively. We use a random sequence of 256-symbols for real-time modulation. The intensity of the source is heavily attenuated to the respective single photon levels, 0.5 and 0.4 photons/ns. Temperature-controlled planar lightwave circuit Mach-Zehnder interferometers with 3 dB optical loss are used for phase decoding, and superconducting nanowire detectors are used for single photon detection. To compute the secure key rates, we follow the equations in Refs [3] and [4] for the decoy BB84 and DPS protocols, respectively.

Figure 1(c) shows the results of a QKD experiment using the BB84 protocol, where the sifted key rate and quantum bit error rate (QBER) are directly measured quantities. The experimental values (symbols) are in excellent agreement with theoretical simulation (lines). The maximum transmission loss of 40 dB (equivalent to 200 km of standard single mode fibre) is limited only by the detector noise. The QBER stays approximately constant at a base level of 2.4% for channel losses up to 30 dB. This base value sets an upper bound for the encoding error of the light source as a BB84 encoder, which is comparable to the values achieved with conventional bulk or fibre optics [3]. Figure 1(d) shows the results for the DPS protocol. The base QBER of 1.9% is well within the error threshold of the protocol. We also measure the performance over a 100 km fibre spool, observing very similar error and bit rates to using the equivalent optical attenuation shown by the red data points in the plot.

We have demonstrated a novel directly phase-modulated light source which permits the preparation of pure phase states with an exceptionally low driving voltage and which is suitable for QKD. In the future the phase-modulated source could be integrated into a fully-functional phase transmitter with a size comparable to small-form pluggable transceiver modules (SFPs) ubiquitously found in today's communication systems. Integration at this level is highly desirable, and will find applications in heterogeneous networks where different quantum communication protocols coexist [5] or in access networks where the compactness and cost of the transmitters is of paramount importance [6].

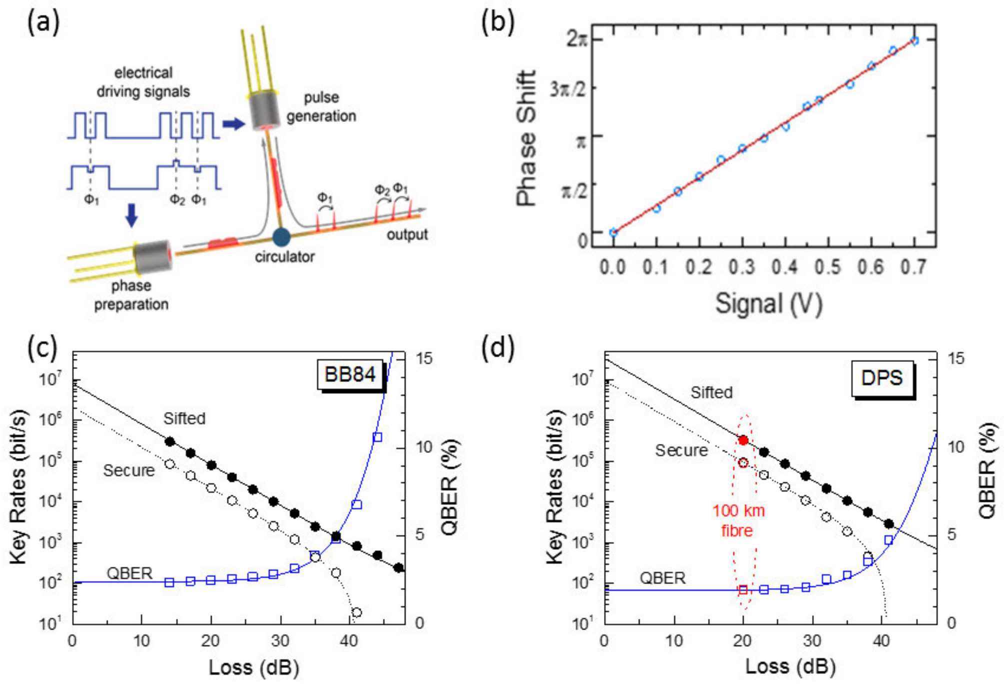


**Figure 1** (a) Directly phase-modulated light source. The source consists of a pair of semiconductor laser diodes connected via an optical circulator and driven from specific electric patterns. We refer to these laser diodes as the phase preparation and pulse generation lasers. The phase preparation laser is biased to produce nanosecond scale, quasi steady-state optical pulses superimposed with shallow intensity modulation. The pulse generation laser is gain-switched to generate short optical pulses which inherit the optical phase prepared by the phase preparation laser. The duration of each seed pulse can be varied to seed a pulse train of different lengths, and the relative phase between consecutive short pulses are defined by the modulation depth of the phase preparation laser. (b) Phase shift as a function of the electrical signal amplitude applied to the phase preparation laser. (c) Experimental results (symbols) and simulation (lines) of the BB84 protocol. (d) Results for the DPS protocol.

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