Modulator-free intensity- and phase-modulated optical transmitter for quantum communications

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Abstract: We demonstrate a simplified optical transmitter design for generating intensity- and phase-modulated pulses, using injection locking and pulse interference. The transmitter is applied for proof-of-principle quantum key distribution, achieving Mbps secure bit rates.

1. Introduction

The generation and modulation of short pulses of light underpins optical fibre communications. High-performance, compact optical transmitters are widely available and optimised for many different classical communication protocols. In recent years, however, there is growing demand for new optical transmitters with very different requirements to satisfy the needs of emergent quantum communication protocols [1]. Quantum key distribution (QKD) is the most successful example of quantum communications to date, enabling quantum-safe data transmissions that are resistant to the threat that quantum computers pose to conventional asymmetric cryptography [2].

QKD transmitters typically generate attenuated laser pulses (‘coherent states’) and often implement the BB84 protocol, with decoy states to defend against the well-known photon number splitting attack [3]. There is thus strong demand for high-speed optical transmitters that can generate pulses with phase modulation (for encoding bit and basis values) and intensity modulation (for creating ‘decoy states’ by varying the intensity between a few discrete levels). Another requirement for the security of QKD is that the phase of each pulse is globally random. These stringent requirements are driving research into new optical transmitters for quantum communications.

Conventionally, optical pulses for QKD are generated by carving short temporal bursts out of a CW laser using an intensity modulator. Numerous subsequent phase and intensity modulators are then required to modulate the pulse amplitude and phase with high precision (often back-to-back modulators are required to achieve sufficient extinction ratio and linearity [4]), e.g. Fig. 1a. While such optical setups have been demonstrated for QKD applications, the need for chains of modulators (each with associated driving electronics) is costly and complex, as well as hampering the potential for photonic integration due to the use of bulk $LiNbO_3$.

Recently, it has been shown that gain-switched lasers and injection locking can be used to generate phase-modulated short pulses with a globally random phase [5]. However, the need for a bulk intensity modulator remained to implement decoy states. Here, we introduce a new optical transmitter design that solves this problem, carefully exploiting laser dynamics and interference to generate phase- and intensity-modulated pulses.

2. Optical Transmitter Design

Our transmitter (Fig. 1b) comprises 2 gain-switched semiconductor DFB lasers (at 1550 nm) in a primary-secondary (master-slave) injection-locking arrangement. The primary laser is pulsed at 667 MHz, generating pulses with a random phase since the laser is forced below threshold between pulses. These are injected to injection-lock the secondary laser, which is pulsed at 2 GHz (where the phase is inherited from the injected primary laser pulse). Modulations are then applied to the electrical driving signal, which perturbs the laser cavity dynamics and temporarily shifts the wavelength, and thus, varies the phase. Finally, we use an asymmetric Mach-Zehnder interferometer (AMZI) to interfere consecutive pulses, resulting in output pulses whose intensity depends on the phase difference of the 2 input pulses. By carefully harnessing the dependence of laser phase upon electrical driving pattern, we can precisely control the phase between the 3 pulses that are generated by the secondary laser for each injected primary pulse (while ensuring the global phase for each triplet is random), and thus, following interference, the intensity (Fig. 1c) .

The transmitter clock rate is equal to the primary laser pulsing frequency and during each clock cycle, 3 pulses are outputted from the interferometer. One pulse in the output triplet has a random phase and intensity, since it results from interference between secondary pulses from different primary pulses (i.e. with random, uncontrolled

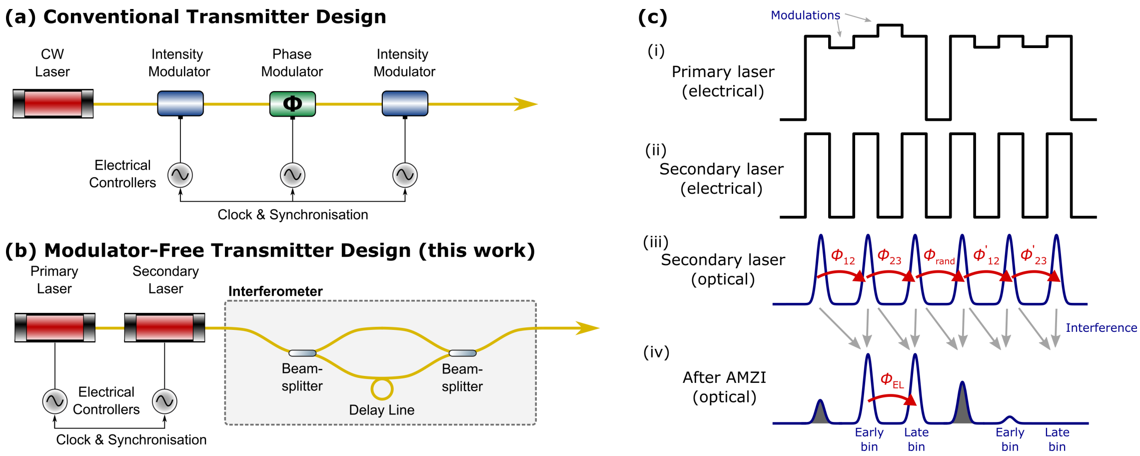

Fig. 1. (a) Example of conventional modulator-based QKD transmitter; (b) schematic of our simplified transmitter design; (c) schematic illustration of the operating principle of our design.

phase difference). The other two pulses have a deterministically chosen intensity and relative phase difference (while the global phase is random), which makes them ideal to use as the early and late time bin for quantum coherent state encoding (with an attenuator added after the interferometer to reduce the pulse intensity to the single-photon level). Mathematically, the intensity, I of the early (E) and late (L) time bin pulses, and the relative phase difference ϕ_{EL} are given by:

$$I_E = A\cos\left(\frac{\phi_{12}}{2}\right), I_L = A\cos\left(\frac{\phi_{23}}{2}\right), \phi_{EL} = \frac{\phi_{12}+\phi_{23}}{2}$$

Fig 2(a) shows the calculated ϕ_{EL} values for all possible phase differences ϕ_{12} and ϕ_{23} between the input pulses.

The transmitter is well-suited for implementing the time-bin-based decoy-state BB84 QKD protocol, with Z and Y basis encoding, where we choose Y as the majority basis. For Z-basis encoding, a pulse is located in either the early time bin (representing bit 0) or the late time bin (bit 1). Bit 0 is encoded by setting $\phi_{12} = 0$ to produce a pulse with maximum intensity in the early time bin and $\phi_{23} = \pi$ to achieve destruction interference that suppress any light in the late time bin. Similarly, bit 1 can be encoded by choosing $\phi_{12} = \pi$ and $\phi_{23} = 0$. Z-basis decoy states are generated similar to the above, but instead of using zero relative phase which results in a pulse with maximum intensity, a lower intensity can be generated by choosing a relative phase close to π—e.g. a decoy bit-0 state with an intensity of 0.1 (relative to the signal state) can be generated by choosing $\phi_{12} = 0.9\pi$ and $\phi_{23} = \pi$.

For Y-basis encoding, a single bit is a superposition of early and late time bins with a relative phase of $\pi/2$ (bit 0) or $3\pi/2$ (bit 1). To ensure equal intensity of early and late time bins, it is necessary that $\phi_{12} = \phi_{23}$. Thus, to encode bit 0 with $\phi_{EL} = \pi/2$, $\phi_{12} = \phi_{23} = \pi/2$. Similarly, for bit 1 with $\phi_{EL} = 3\pi/2$, we use $\phi_{12} = \phi_{23} = 3\pi/2$. Our transmitter design is therefore a highly flexible approach to adjust the intensity and phase of pulses by only controlling the electrical waveforms applied to the lasers; no bulk modulators are required.

We implemented our design experimentally and confirmed that all the desired QKD encoding states could be generated. Modulation features with a width of 150 ps were applied to the primary laser's driving waveform while the secondary laser was off, changing the primary laser's phase and thus, the secondary laser's phase (through injection locking) when it was next turned one. As the magnitude of modulation voltage applied to the primary laser was varied, we observed a linear change in the relative phase between the secondary laser pulses (Fig 2b) which resulted in the expected cosine curve for pulse intensity as a function of modulation voltage at the output of the interferometer (Fig 2c). It should be noted that the modulation voltages required to achieve a π phase shift are <1 V which is lower than the few-volt level typically needed to drive bulk $LiNbO_3$ modulators.

In order to achieve high-coherence phase transfer from the primary to the secondary laser, it is important to optimise the injection locking conditions, including the relative free-running wavelengths of the two lasers and the injection power. Due to the complex nonlinear laser dynamics involved, this can be a complicated optimisation problem, although it has recently shown this can be solved using machine intelligence techniques [6].

3. QKD Demonstration

After characterising the optical transmitter, we demonstrated its suitability to quantum communication protocols by performing proof-of-principle BB84 QKD with 2 decoy states. Fig. 3a shows the full optical setup schematically, where the receiver implements a random passive basis choice using a beam splitter. Z-basis measurements

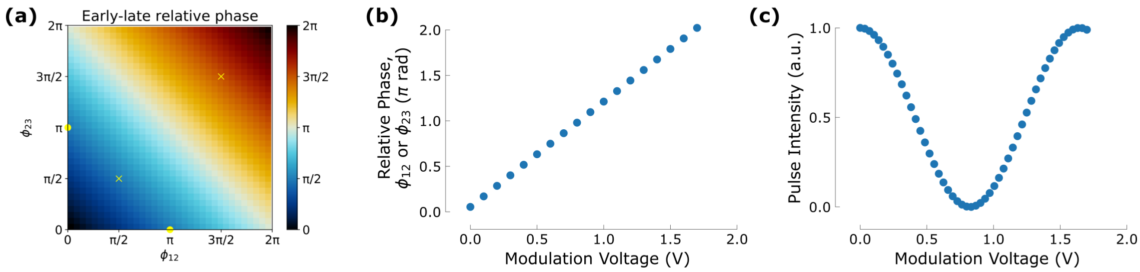

Fig. 2. (a) Impact of phase differences for two input pulses on the interferometer output; (b) Measured output relative phase and (c) intensity vs modulation voltage.

are made by directly detecting photons using a superconducting nanowire single-photon detector (SNSPD, 70% efficiency, 50 Hz dark counts). Y-basis measurements are made by interfering the early and late time bins of a state in an AMZI, followed by 2 SNSPDs. All SNSPDs are connected to a time-tagger and the resulting measurements are processed to extract the quantum bit error rate (QBER) and to compute the secure bit rate of the QKD system assuming an asymptotic analysis, as the channel attenuation is varied (Fig. 3b). A secure bit rate of 2.21 Mbps is recorded at 15 dB (~75 km fibre equivalent), showing the suitability of the setup for metro-scale QKD networks.

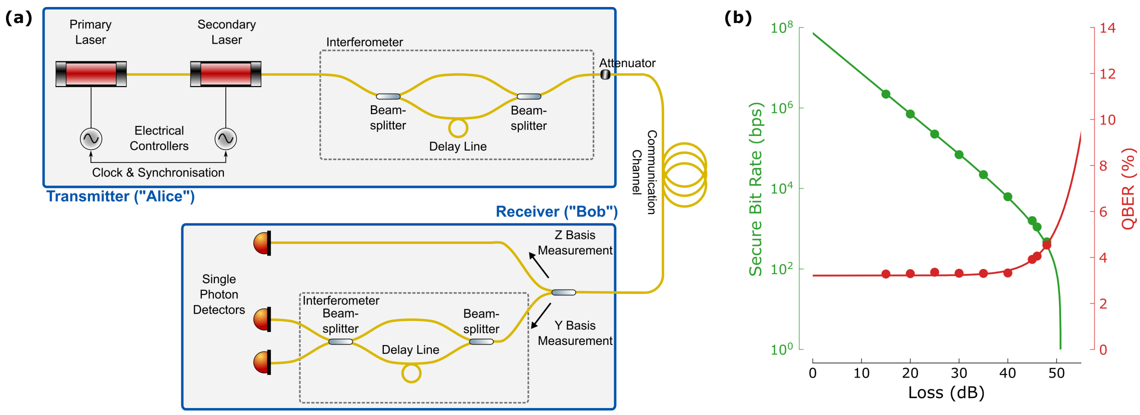

Fig. 3. (a) Experimental QKD schematic; (b) secure bit rate and QBER as a function of loss (markers: experimental data; lines: simulations).

4. Conclusion

We have developed an optical transmitter design for generating intensity- and phase-modulated pulses, without bulk modulators. By careful choice of laser driving waveforms, the transmitter can generate appropriate states for decoy-state BB84 and we demonstrated proof-of-principle QKD with >1 Mbps secure bit rates. Such simplified optical transmitters pave the way to more widespread deployment of quantum communication technologies.

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