Reconfigurable Frequency Coding of Deterministic Single Photons in the Telecom C–Band

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Abstract: In this work, we develop reconfigurable frequency manipulation of quantum states of light in the telecom C–band. Deterministic single photons are encoded in a superposition state of three tunable channels using sidebands spanning 53 GHz created by an off–the–shelf phase modulator. The single photons are emitted by an InAs/GaAs quantum dot grown by metal-organic vapor-phase epitaxy within the transparency window of the backbone fiber optical network. This combination of established telecommunication equipment and a novel quantum light source paves the way for future quantum-internet applications.

1. Introduction

Quantum information science is an interdisciplinary field wherein quantum mechanics sets rules for logical bits (qubits), gates and interconnects [1]. Transferring quantum information between stationary nodes is one of the requirements to scale the field beyond isolated locations [2].

Qubit teleportation protocols [3–5] or direct state transfer methods [6, 7] between two nodes are commonly built based on single photons, so called "flying qubits". Photons at a wavelength of 1.55 µm [8] (C–band) can travel over large distances in optical fibers and are ideal candidates to distribute entanglement or exchange quantum information between distant network nodes, known as "quantum internet" [2, 9]. The advantage of pre–existing infrastructure for optical classical communication networks [10] leads to faster and cheaper adoption of quantum communication.

Semiconductor quantum dots (QDs) are a promising sources for flying qubits at 1.55 μm [11–13], due to the deterministic emission of single photons [14] and polarization entangled photon pairs [15, 16]. The quantum dot growth via metal–organic vapor–phase epitaxy enables industrial large–scale fabrication in future photonic quantum technology applications. By combining this industry grade growth technique with nanofabrication methods, QDs establish themselves as scalable, integratable [17] and tunable sources for the C–band [18]. As compared to the standard InP–based materials for this wavelength range, the choice of InAs/GaAs quantum dots has several advantages regarding the optical properties of the quantum dots and the possibilities for cavity–enhanced emission enabling ultra-high repetition rates [12, 19].

Building up multi–node quantum networks requires multiple sources which need to be tuned in resonance to one another within their natural linewidth or wavelength-multiplexed in the same fiber for enhanced quantum communication bandwidth and multiple access options. Thus,

dynamically manipulating single photon properties such as frequency or line–shape is a key requirement for quantum information science. Although, attenuated coherent carriers with sidebands were proposed and used for Quantum Key Distribution [20], moving to flying qubits with high purity number states enables new applications, e.g. phase–modulated single photons are suggested for frequency–based linear optical quantum computing [21] and frequency-based higher order entangled states [22]. Constructing a flying qubit Hilbert space in frequency domain is bound to boost quantum data communication bandwidth, following the steps of classical optical communication where generally a combination of time-division coding and frequency-division coding is used for high data-rate applications. The possible on-demand generation [23] of single photons with InAs/GaAs QD coupled with the frequency coding we develop here, using off-the-shelve components, makes the platform ideal for long distance and high bandwidth quantum communication.

Paudel et al. [24] recently demonstrated the preservation of indistinguishability of near-infrared photons emitted by a quantum dot through phase modulation. We extend this result and move to a triggered QD system with an emission in the standard telecom 1.55 μm band. We experimentally demonstrate triggered generation, manipulation and transmission of single photons in the telecom C–band. We create a superposition state spread over three adjacent channels (26.5 GHz separation), which we then transfer over data–center distance (1.6 km). The transmission link consists of an InAs/GaAs quantum dot source, an off-the-shelf phase modulator and telecom single mode fibers (SMF–28). We show that the sideband photons generated with the phase modulator follow the properties of the unmodulated photons emitted by a single QD. Our work demonstrates the integration of novel single photon sources with mature telecom technology, allowing large–scale quantum information processing and networking in the 1.55 μm band.
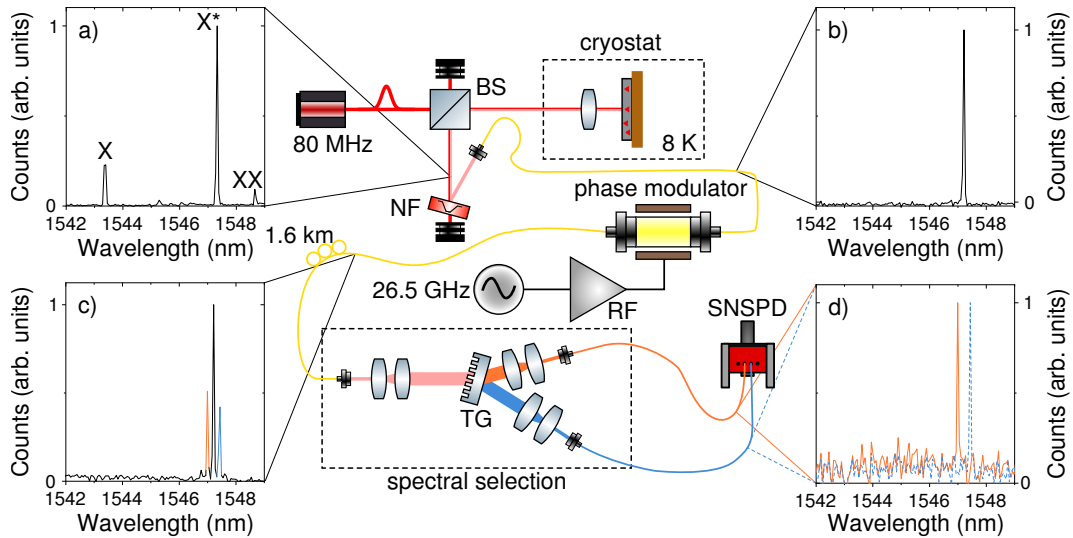

Fig. 1. The setup with spectra at different positions in the experiment. Single photons of a MOVPE–grown InAs/GaAs QD in a closed–cycle cryostat (a) are fiber coupled through a confocal microscope. (b) A notch–filter (NF) is used to reflect one emission line of the quantum dot. (c) The reflected single photons are sent to a phase modulator driven with 26.5 GHz, (d) spectrally filtered using a transmission spectrometer and connected to superconducting nanowire single photon detectors (SNSPD).

2. Experiment

Our experimental setup is described in Fig. 1. The setup consists of MOVPE–grown InAs quantum dots embedded on a stress–releasing metamorphic buffer placed in a close–cycle cryostat with a base temperature of 8 K, and a microscope objective (0.85 NA) as part of our confocal microscopy setup. The quantum dot is excited at 1470 nm with 2 ps pulses and a repetition rate of 80 MHz. Based on spectral measurements, only a specific quantum dot emission line is selectively reflected from a tunable notch filter with a spectral bandwidth of 0.7 nm and a rejection of 40 dB. The filtered single photons are then coupled in an optical fiber connected to the modulation setup. We use a standard LN phase modulator (Sumitomo T.PM1.5–40) to create the sideband photons. The modulator is driven at 5 Vpp to create sidebands at a spectral distance of 26.5 GHz. The quantum signal is sent through a 1.6 km long SMF–28 fiber before the generated sidebands are separated from the carrier using a home–built transmission spectrometer [25]. After passing the transmission grating (TG) the two sidebands (spectrally separated by 0.4 nm) are coupled into two optical fibers that are connected to superconducting nanowire single photon detectors (15 % and 25 % efficiency with 30 dark counts per second). To record the correlations between the single photon sidebands a correlator (50 ps time jitter between channels) is used. Additionally, a spectrometer (750 mm focal length, 830 l/mm grating) and an InGaAs array are used for the spectral analysis.
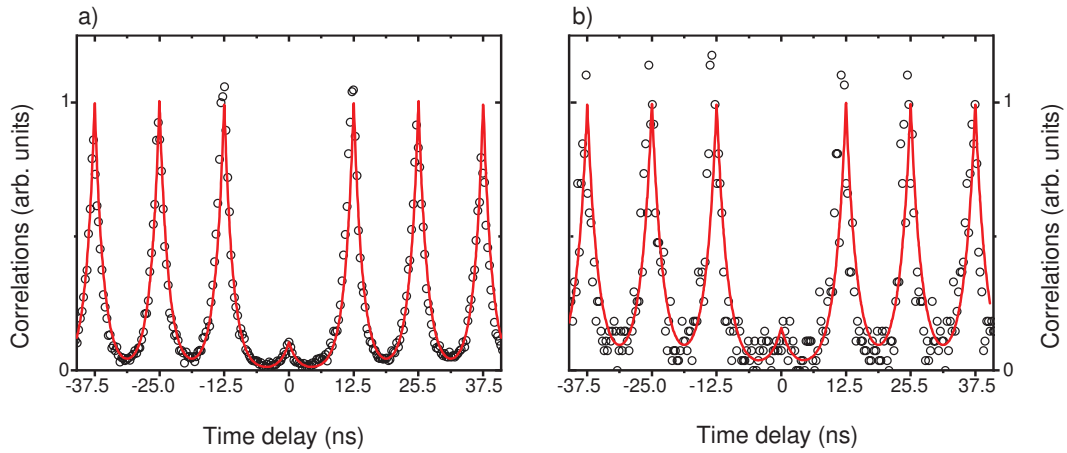

Fig. 2. (a) Auto–correlation measurement on the photons emitted into the charged exciton line X* (1547.21 nm) filtered by the notch–filter yielding a multi–photon probability of $g^{(2)}(0) = 0.11 \pm 0.03$. (b) Cross–correlation measurement between the two sidebands at 1546.99 nm and 1547.42 nm. The open circles represent the measurement data, the solid lines correspond to a fit to the data.

3. Results

In a QD, the emission is related to the particles involved in the recombination process. A systematic study, including power and polarization dependent measurements [18], was performed to identify three optical transitions X, XX, and X* in the spectra. After excitation, the s–shell of our source can be filled with two electrons in the conduction band and two holes in the valence band. This can result in the emission of a biexciton photon via the recombination of one electron–hole pair, labeled XX. The remaining electron and hole pair in the QD recombines to emit an exciton photon, labeled X. Additionally, the QD can trap a single electric charge in the presence of an electron–hole pair, the three-particle complex produces a trion, labeled X*. A

spectrum of our source is shown in Fig. 1 (a). All spectra are normalized to their peak value. We select the trion (X*) line emitted by the quantum dot by reflecting only this wavelength (1547.21 nm) on the tunable notch filter. The filtered spectrum is depicted in Fig. 1 (b). We would like to note, that the common insertion loss of commercial telecom equipment on the order of at least 3dB per element, which can be easily compensated in classical communication, is a significant challenge for experiments with single photons.

The multi-photon emission probability of our source is measured by performing a Hanbury Brown and Twiss measurement. To this end, we send the filtered X* photons onto a beam splitter and measure the difference in arrival time between the beam splitter outputs with two superconducting nanowire single photon detectors. This yields the histogram shown in Fig. 2 (a).

The absence of the peak at zero time delay demonstrates triggered single photon emission in the telecom C-band with low multi–photon probability of $g^{(2)}(0) = 0.11 \pm 0.03$. The zero delay multi-photon probability $g^{(2)}(0)$–value is extracted by fitting the correlation peaks and comparing the area between the peak at zero time delay and the side peaks. Using our current excitation method, we can extract the emission decay time which sets the maximum duty cycle of our source to be 1.37 ns $\pm$ 5 ps. This value can be drastically reduced by performing resonant excitation of specific optical transitions [26] and enhancing this emission through an optical cavity structure [19].
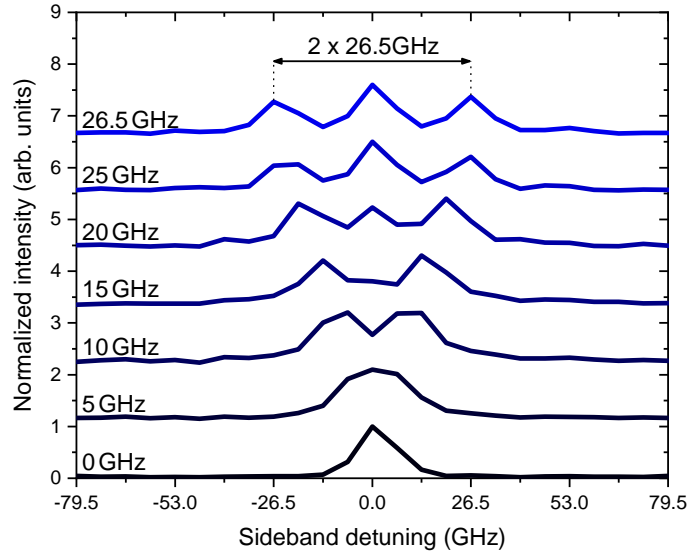

Fig. 3.   Tunable modulation of single photon carriers between 0 and 26.5 GHz creating upper and lower sidebands with variable separation. The emission of the carrier line is at 1547.21 nm.

The ideal trion state for our experiment after the modulation is a superposition state of three frequency channels $|state\rangle = 1/\sqrt{2}\,|carrier\rangle + 1/2\,|carrier + f\rangle + 1/2\,|carrier - f\rangle$. We approximate this state using phase modulation with a single frequency that creates side-bands at multiples of f following the ratio of Bessel functions of the first kind. Therefore we are interested into the first order sidebands and want to minimize the photons lost in higher order sidebands. Using single–frequency phase modulation of 26.5 GHz, and a modulation index of 0.37π, we shift 47.0 % of the photons into the higher (23.5 %) and lower (23.5 %) sidebands

(1547.21 nm ± 26.5 GHz) and loose 4.5 % to higher order sidebands (Fig. 1, (c)). The separation of the sidebands is tunable between 0 and 26.5 GHz (Fig. 3) and can be aligned to a chosen channel spacing. This separation is mainly limited by the signal generator (26.5 GHz) and the modulator (40 GHz). Recent demonstrations by Mercante et. al. show modulations speeds up to 500 GHz or ±4 nm at 1550 nm [27], demonstrating the potential of this technique.

We include 1.6 km of optical fiber between the phase modulator and the spectral filtering of the two sidebands and demonstrate our setup can bridge intra–data center distances. Spectral filtering with the transmission spectrometer allows to separate the sidebands from each other, as shown in Fig. 1 (d). The emission time setting the maximum duty cycle of the photons in lower and upper sideband are measured to be 1.39 ns ± 6 ps and 1.39 ns ± 6 ps respectively. This value is the same as for unmodulated photons within our measurement accuracy. To determine whether our modulation technique is altering the single photon emission of the quantum dot, we perform a cross–correlation measurement between the two sidebands. After spectrally separating the sidebands from each other we measure the time difference between the arrival of the photons in the sidebands. As they are generated from single photons, the peak at zero time delay should still vanish as in the initial measurement. The two sidebands show a correlation probability of $g^{(2)}(0) = 0.16 \pm 0.06$, demonstrating single photons in both sidebands.

4. Conclusion

We showed the use of a deterministic single–photon source based on MOVPE–grown InAs/GaAs quantum dots with standard telecom equipment in the C-band bridging 1.6 km distance. The widely available equipment, already installed infrastructure and the low losses in fibers highlight the importance of this wavelength range for quantum communication. We created single photons with tunable sidebands (up to 53 GHz separation) with a multi–photon emission probability in the sidebands of $g^{(2)}(0) = 0.16 \pm 0.06$. This can be seen as a single photon source multiplexed on several channels or can be used as a resource for a frequency based qubit. With standard IQ modulators, a similar technique allows to shift the carrier [28] to fine-tune the overlap with another source. We demonstrate the transmission of this single-photon resource over intra–data-center distances allowing the modularisation of experiments in a future quantum computation hub.

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