High visibility Hong-Ou-Mandel interference from weak-coherent pulses generated by III–V on silicon waveguide integrated lasers

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Abstract: Gain-switched III–V on silicon waveguide integrated lasers are used to generate weak-coherent pulses compatible with high rate Quantum Key Distribution (QKD) and, by exhibiting Hong-Ou-Mandel interference with $46 \pm 2\%$ visibility, suitable for Measurement-Device-Independent-QKD.

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1. Introduction

Quantum Key Distribution (QKD), the most technically advanced application of quantum communications, allows two parties to distill a common cryptographic key with provable unconditional security [1], enabling safe exchange of sensitive data. Attracted by the scalability, compactness and optical stability offered by silicon photonic integrated circuits (PICs), QKD has been increasingly allured by such platform [2, 3]. However, the integration of simple high repetition rate photon sources is yet to be achieved and several challenges remain, mainly in terms of scalability and losses. The use of weak-coherent pulses (WCPs), generated by attenuating laser light, represents a viable solution for QKD since it can be securely implemented with WCPs using the decoy-state technique [1]. Therefore, the integration of III–V lasers on silicon PICs, compatible with CMOS fabrication and the industrial requirements for mass production [4], offers a promising prospect for quantum photonics.

We demonstrate, for the first time, the use of a gain-switched III–V on silicon waveguide integrated laser to generate WCPs.The generated WCPs are compatible, in terms of repetition rate and pulse duration, with the requirements for high rate QKD. Furthermore, we demonstrate that the WCPs generated by independent gain-switched III–V on silicon waveguide integrated laser exhibit high-visibility Hong-Ou-Mandel (HOM) interference [5]. The observation of this versatile quantum optics effect is a requirement for Measurement-Device-Independent-QKD, a protocol immune to detector side channel attacks and suitable for long-haul fibre-optic implementations [6].

2. Experimental setup and results

The lasers used in this experiment were Distributed Feedback (DFB) based on Indium Phosphide heterogeneously integrated on silicon trough molecular wafer bonding, lasing linearly polarized light at 1534.5 nm. This hybrid III–V on silicon technology was fabricated as described by Duan *et al.* [7].

The lasers were independently probed and operated in gain-switching mode, generating short optical pulses with random phase and 100 MHz repetition rate. A grating coupler in the silicon waveguide was used to couple the emitted light into single-mode optical fibers. To remove the detrimental effects of the chirp commonly observed in gain-switched semiconductor lasers [8], the laser light was then filtered using a tunable filter with 100 pm bandpass (BPTF). Lastly a variable optical attenuator is used to make WCPs with mean number of photons $\mu \approx 10^{-2}$.

The temporal profile of the single photon detection of the WCPs was obtained using a InGaAs/InP single-photon avalanche diode (SPAD) manufactured by Micro Photon Device S.r.l. [9] and a time-to-digital converter with 1 ps resolution. As reported in figure 1(a), a full width at half maximum (FWHM) $\approx$ 145ps is observed. This corresponds to the convolution between the response functions of the SPAD and of the time-to-digital converter with the temporal profile of the WCPs. The solid line is obtained by fitting the data with the detector response function [9]. Such temporal duration would allow for WCP generation at high repetition rates of up to few GHz.

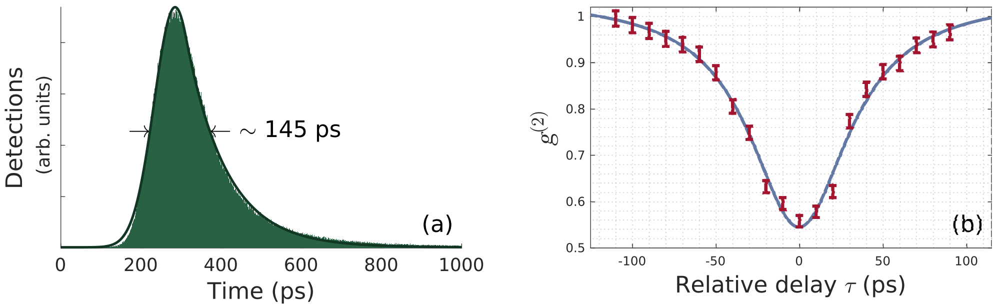

Fig. 1. (a) Temporal profile with 145 ps FWHM. (b) HOM dip with visibility $\mathscr{V} = 46 \pm 2\%$.

To observe HOM interference between WCPs generated by gain-switched III-V on silicon waveguide integrated lasers an optical delay-line (ODL) was placed in the optical path of one the WCPs, allowing to match the time-of-arrival of the photons and to scan the HOM dip. Polarization controllers (PCs) were then placed to guarantee identical polarizations. The WCPs were then combined with a 50/50 beam-splitter (BS). The output ports of the BS were connected to the SPADs and the detection events were sent to a coincidence logic that allowed to estimate the value of the $g^{(2)}(\tau)$ intensity-intensity correlation as a function of the relative delay τ imposed by the ODL . Due to the shape of the BPTF, the HOM dip follows a Lorentzian shape, and is of the form

$$g^{(2)}(\tau) = 1 - \mathscr{V} \frac{(\frac{\Gamma}{2})^2}{\tau^2 + (\frac{\Gamma}{2})^2} \tag{1}$$

with visibility $\mathscr{V}$, and HWFM Γ. As reported in figure 1(b), a visibility $\mathscr{V} = 46 \pm 2\%$ is estimated from the fit with equation (1). Such visibility is compatible with the theoretical visibility obtained when considering detector imperfections [10], and sufficient to obtain a positive secret key rate in MDI-QKD [8].

3. Conclusions

Envisioning a compact PIC which integrates *all* required components to generate WCPs exhibiting high-visibility HOM interference is a realistic short-term goal and is closer and closer to fulfill industrial requirements for mass production, since bandpass filters and variable attenuators have already been integrated into silicon PICs. Such WCP generator PIC could be further integrated into quantum state encoder PICs, using polarization or time-bin degrees of freedom [3], resulting in a compact silicon PIC capable of performing both MDI-QKD or standard QKD protocols. This result paves the way for the implementation of QKD networks fully based on integrated silicon photonics.

References

1. V. Scarani *et al.*, *The security of practical quantum key distribution*, Rev. Mod. Phys. 81, 1301 (2009).
2. Y. Ding *et al.*, *High-dimensional quantum key distribution based on multicore fiber using silicon photonic integrated circuits*, npj Quantum Inf. 3, 25 (2017).
3. P. Sibson *et al.*, *Integrated silicon photonics for high-speed quantum key distribution*, Optica **4**, 172 (2017).
4. B. Szelag *et al.*, *Hybrid III–V/Si DFB laser integration on a 200 mm fully CMOS-compatible silicon photonics platform*, 2017 IEEE International Electron Devices Meeting (IEDM), pp. 24.1.1 - 24.1.4.
5. C. K. Hong, Z. Y. Ou, L. Mandel, *Measurement of subpicosecond time intervals between two photons by interference*, Phys. Rev. Lett. **59**, 2044 (1987).
6. H.-K. Lo, M. Curty, B. Qi, *Measurement-Device-Independent Quantum Key Distribution*, Phys. Rev. Lett. **108**, 130503 (2012).
7. G.-H. Duan *et al.*, *Hybrid III–V on Silicon Lasers for Photonic Integrated Circuits on Silicon*, IEEE J. Sel. Top. Quantum Electron. **20**, 158 (2014).
8. Z.-L. Yuan *et al.*, *Interference of Short Optical Pulses from Independent Gain-Switched Laser Diodes for Quantum Secure Communications*, Phys. Rev. Applied **2**, 064006 (2014).
9. A. Tosi *et al.*, *Fully programmable single-photon detection module for InGaAs/InP single-photon avalanche diodes with clean and sub-nanosecond gating transitions*, Rev. Sci. Instrum. **83**, 013104 (2012).
10. E. Moschandreou *et al.*, *Experimental Study of Hong-Ou-Mandel Interference Using Independent Phase Randomized Weak Coherent States*, J. Light. Technol. **36**, 3752 (2018).