Implementation of an efficient linear-optical quantum router

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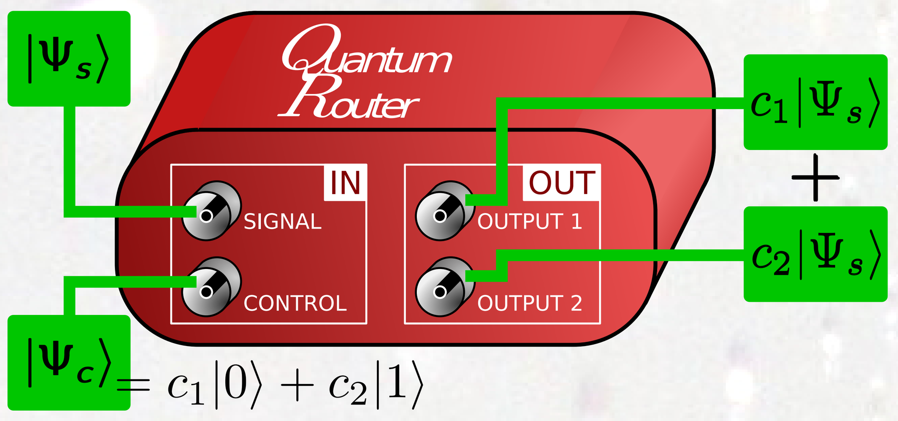
What is a quantum router?

- A quantum router is one of the key components of future quantum networks.
- The device has two inputs – the signal and control qubits denoted $|\psi_s\rangle$ and $|\psi_c\rangle = c_1|0\rangle + c_2|1\rangle$, respectively.
- Based on the quantum state of the control qubit, the signal is coherently forwarded to two output ports.
- Conditions:
  1. signal and control have to be quantum states
  2. quantum state of signal has to be unchanged
  3. the router splits the signal into coherent superposition of both output ports
  4. no postselection, success of probabilistic device heralds control state detection
  5. only one control for each signal qubit



- Properties of interest: probability of success of routing procedure, routing efficiency (contrast ON/OFF), fidelity of output states, degree of coherence between outputs

References

Why to use linear optics? – straightforward implementation into quantum-optical (e.g. single photon) communication networks

- Opt. Comm. **300**, 282 (01/2013) – two identical ancilas needed, maximal achievable probability of success 1/4 (with feed forward), *proposal realized in this work*
- Phys. Rev. A **87**, 062333 (06/2013) – only one ancila, routing by tunable c-phase gate, probability of success depends on the input state and routing ratio ranging from 1/8 to 1/24
- Nat. Photon. **7**, 521 (7/2013) – linear-optical realization of quantum state fusion (similar to routing) with probability of success 1/8
- Phys. Rev. A **90**, 012331 (2014) – study of quantum-walk architecture and its routing capabilities

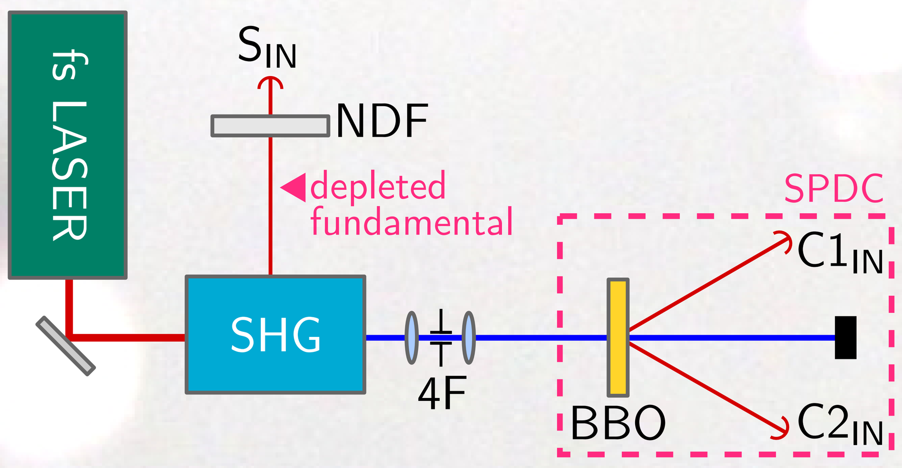
The others:

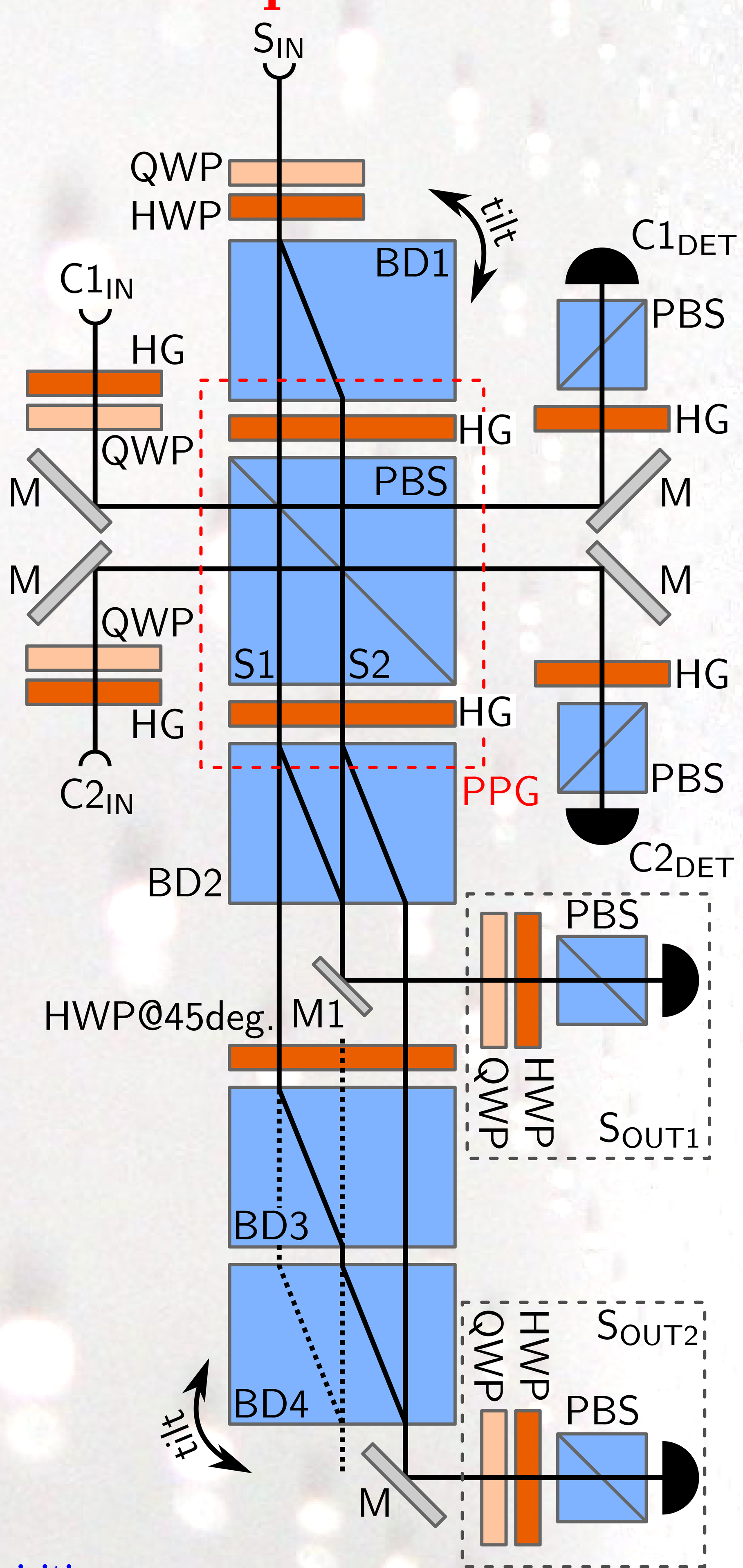
- Phys. Rev. A **80**, 042303 (2009) – spin chain
- Phys. Rev. A **89**, 013805 (2014) – atoms
- Scient. Rep. **4**, 4820 (2014) – two-level systems
- Scient. Rep. **6**, 27033 (2016) – quantum dots
- Scient. Rep. **6**, 39343 (2016) – coupled cavity
- Opt. Express **25**, 16931 (2017) – nitrogen-vacancy center

Experimental setup

Three photon source

- pump – femtosecond laser, wavelength 826 nm, spectral width 10 nm (FWHM), repetition rate 80 MHz
- collinear second harmonics generation
- depleted fundamental attenuated by neutral density filters (NDF) to single photon level – used as a signal
- second harmonics at 413 nm (filtered by band-pass filter to 10 nm FWHM), spatially filtered by 4F system, mean power 100 mW, pump type-I BBO crystal
- two control photons are generated by spontaneous parametric down-conversion
- all three modes are filtered spectrally by band-pass filters with 3 nm FWHM and spatially by single-mode fibers



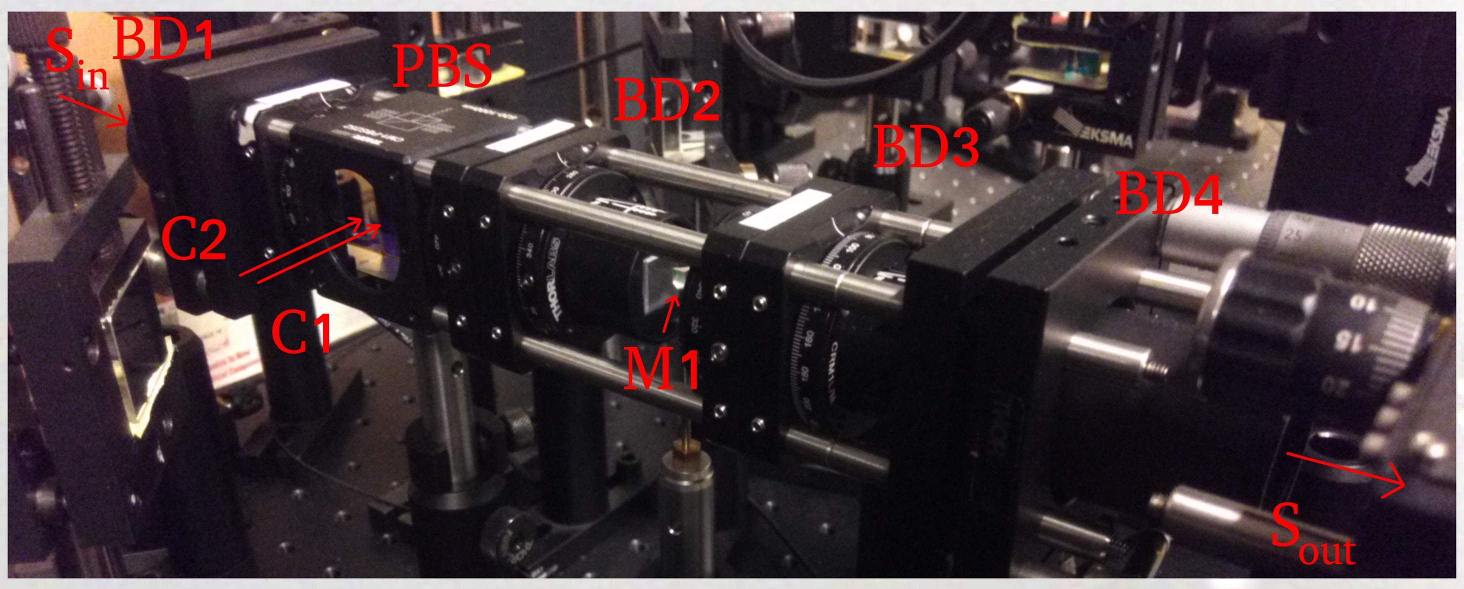


Working principle

- quantum states are encoded into polarization states of single photons: $|0\rangle \equiv |H\rangle$, $|1\rangle \equiv |V\rangle$
- BD splits photons into two spatial mode with respect to their polarization, four BDs form very stable two nested Mach-Zehnder interferometers
- block formed by two half-wave plates rotated by 22.5 deg. (HG) and polarizer (PBS) serves as programmable phase gate
- both control qubits are projected into horizontal polarization, with no feed forward the router have probability of success 1/16

Data acquisition

- three-fold coincidences between the first or the second signal output and two control output were measured
- due to the imperfections of the three photon source (more than one photon to each mode) accidental coincidence occurs, their rates were measured by sequential blocking of each mode, raw data means without correction on the imperfection of the source



Conclusions

- We build quantum router which satisfy 4/5 of conditions needed. The problem with two control qubits can be solved unless they are obtained from a computationally difficult operation.
- The right operation of routing was proved: mean corrected ON/OFF contrast $(15.7 \pm 4.6) : 1$ in the first and $(41.8 \pm 19.7) : 1$ in the second output port, mean corrected fidelity of the output state 0.907 ± 0.038 and $(97.7 \pm 0.3)\%$ coherence between output ports (in terms of visibility).
- Probability of success of this proof-of-principle device was 1/16, using feed forward (measuring also vertical projections of control qubits and using classical switch in output ports) it can reach value 1/4.

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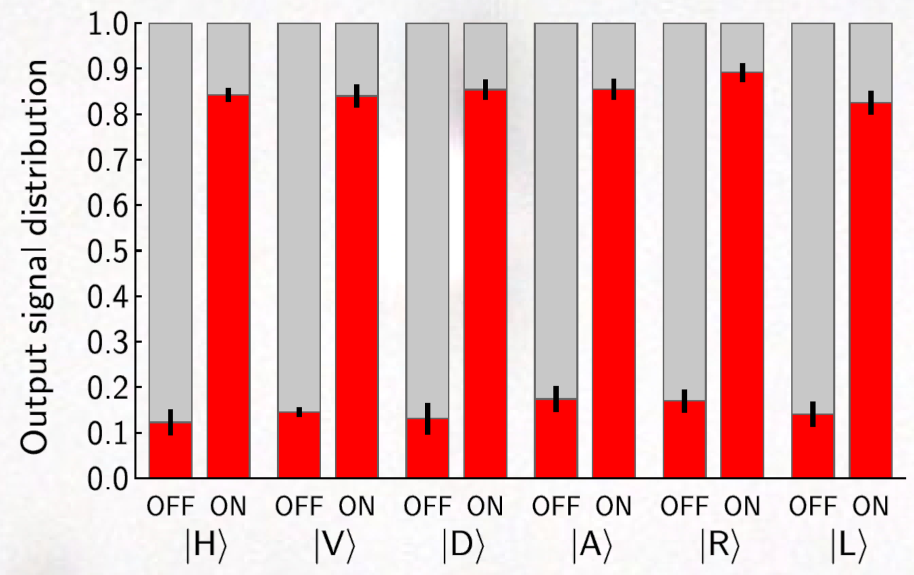
Measurement Results

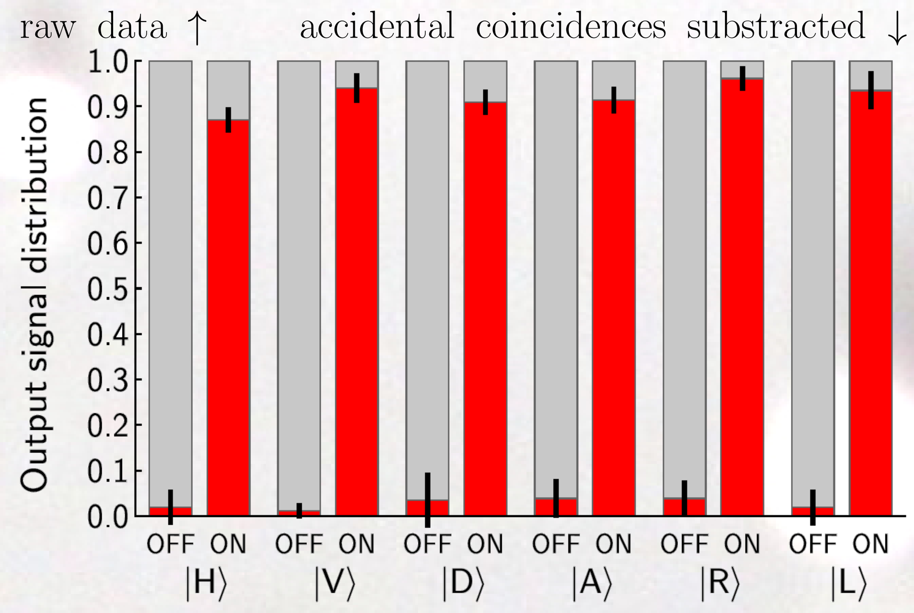
Routing contrast

- control states were set to route the signal solely into the first or the second output
- $|\psi_c\rangle = |0\rangle$ – OFF, $|\psi_c\rangle = |1\rangle$ – ON
- we tested routing efficiency for 6 states of signal qubit
- probability of occurrence of the signal qubit in the second output port P_2 – raw data, P_{C2} – accidental coincidences substracted

signal	control	P_2	σP_2	P_{C2}	σP_{C2}
$\|H\rangle$	OFF	0.123	0.029	0.019	0.039
	ON	0.827	0.024	0.939	0.032
$\|V\rangle$	OFF	0.145	0.011	0.012	0.017
	ON	0.840	0.025	0.940	0.033
$\|D\rangle$	OFF	0.131	0.035	0.035	0.061
	ON	0.854	0.022	0.909	0.028
$\|A\rangle$	OFF	0.174	0.029	0.039	0.043
	ON	0.855	0.023	0.914	0.029
$\|R\rangle$	OFF	0.170	0.026	0.039	0.039
	ON	0.892	0.021	0.961	0.027
$\|L\rangle$	OFF	0.141	0.028	0.019	0.040
	ON	0.825	0.026	0.935	0.042



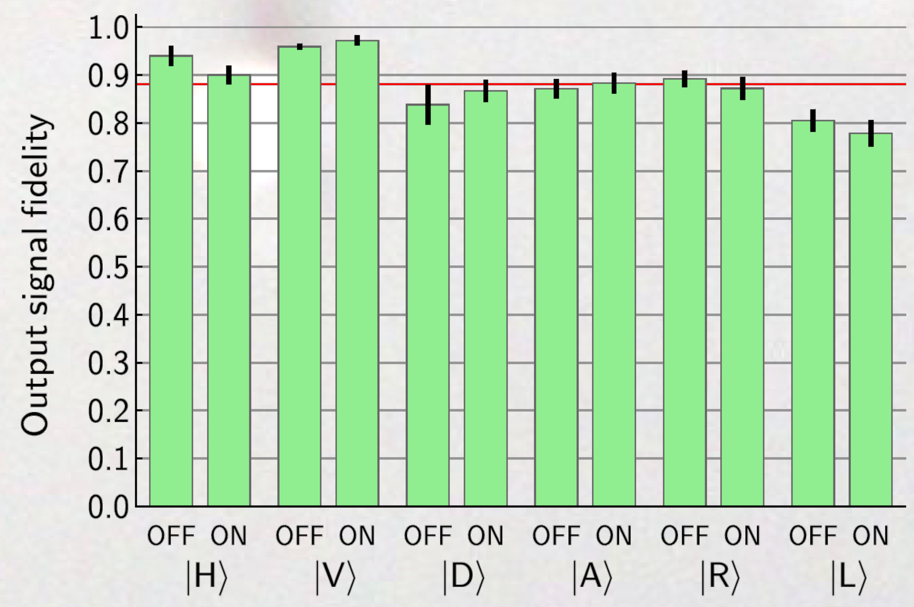
raw data ↑ accidental coincidences substracted ↓



Signal state fidelity

- output signal state disturbance in form of fidelity with the input signal state
- F – fidelity without any correction, F_C – accidental coincidences substracted

signal	control	F	σF	F_C	σF_C
$\|H\rangle$	OFF	0.940	0.021	0.928	0.026
	ON	0.900	0.020	0.899	0.022
$\|V\rangle$	OFF	0.959	0.007	0.947	0.009
	ON	0.972	0.011	0.968	0.013
$\|D\rangle$	OFF	0.838	0.042	0.905	0.040
	ON	0.867	0.023	0.887	0.031
$\|A\rangle$	OFF	0.871	0.021	0.892	0.028
	ON	0.883	0.022	0.951	0.027
$\|R\rangle$	OFF	0.892	0.018	0.914	0.020
	ON	0.872	0.024	0.905	0.033
$\|L\rangle$	OFF	0.805	0.024	0.849	0.029
	ON	0.778	0.028	0.834	0.037
mean		0.881	0.055	0.907	0.038



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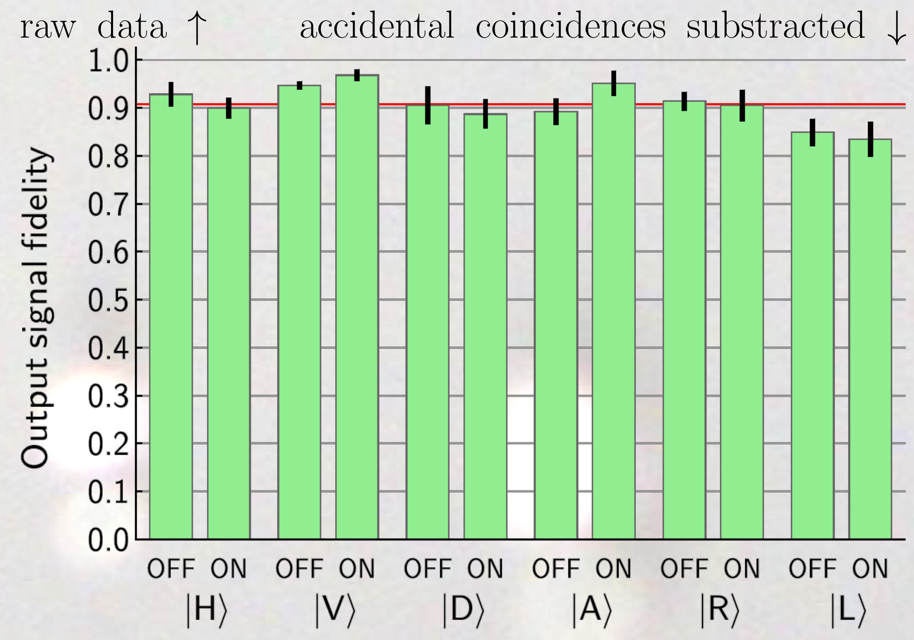

Coherence of output modes

- for the test of the coherence between two output port we mixed two output signal ports on a beam-splitter to form an interferometer and measure the visibility of single photon (first order) interference
- to simplify the measurement we rearrange the setup to do that – we remove M1 and BD3, projection in the second output was set to diagonal linear polarization
- $|\psi_s\rangle = |H\rangle$, $|\psi_c\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$
- we obtain raw visibility of interference fringe 76%, after correction on noise (with value 10.1) we obtain visibility $(97.7 \pm 0.3)\%$ (calculated from fitted sinus function)