Quantum Information Processing (Communication) with Photons

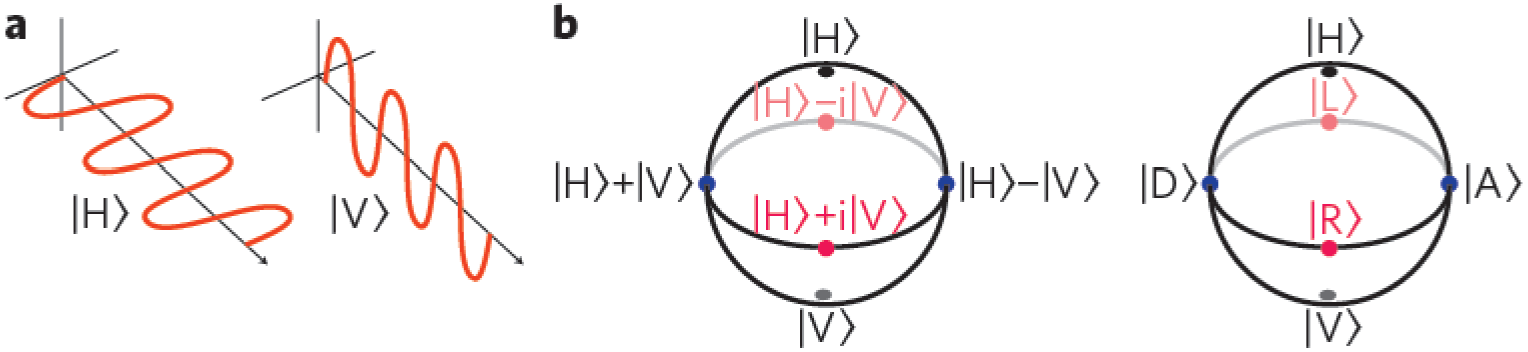
Why Photons?

- only **weak interaction** with environment (good coherence)
- high-speed (c), low-loss transmission ('flying qubits' for **long-distance quantum communication**)
- good **single qubit control** with standard optical components (waveplates, beamsplitters, mirrors,…)
- efficient **photon detectors** (photodiodes,…)
- **disadvantage: weak two-photon interactions**

  (requires non-linear medium -> two-qubit gates are hard)
- use initially entangled quantum state for:
  - (commercial) quantum cryptography
  - *super dense coding*, teleportation
  - fundamental tests of quantum mechanics (*Bell inequalities*)
  - one-way quantum computing

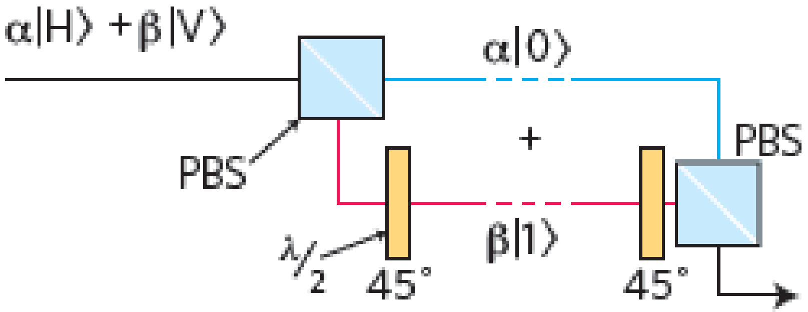
Encoding of quantum information

- polarisation



O’Brien et al., Nature Photonics (2009)

- spatial mode



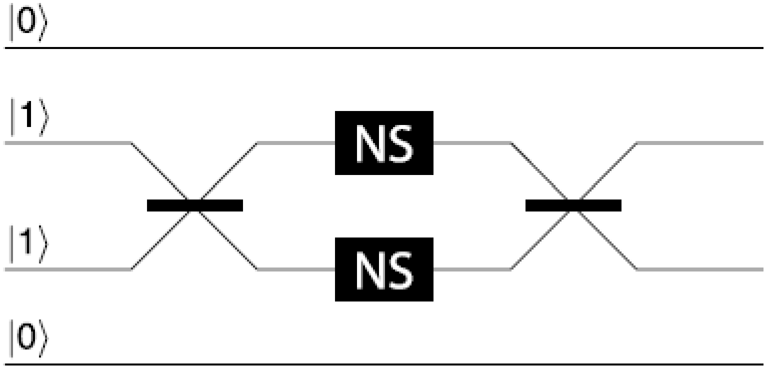
- angular momentum, etc...

Linear Optics Quantum Computation – KLM scheme

Idea: Use only beam-splitters, phase shifters, single photon sources and photo-detectors to implement single and two-qubit gates [Knill-Laflamme-Milburn, Nature 409 (2001)]

Prize to pay: non-deterministic + ancilla photons

optical CNOT-gate based on non-linear sign shift gate (NS)

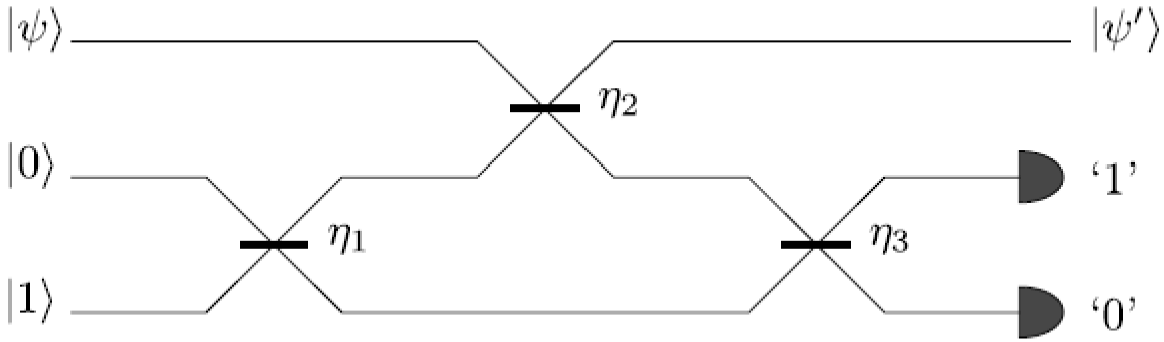


[Kok, 2010]

Linear Optics Quantum Computation – KLM scheme

Non-linear sign gate (NS): $\alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle - \gamma|2\rangle$

effective interaction: projective measurement + ancilla qubits
only if a photon is detected in the upper detector and none in the lower,
the gate was successful



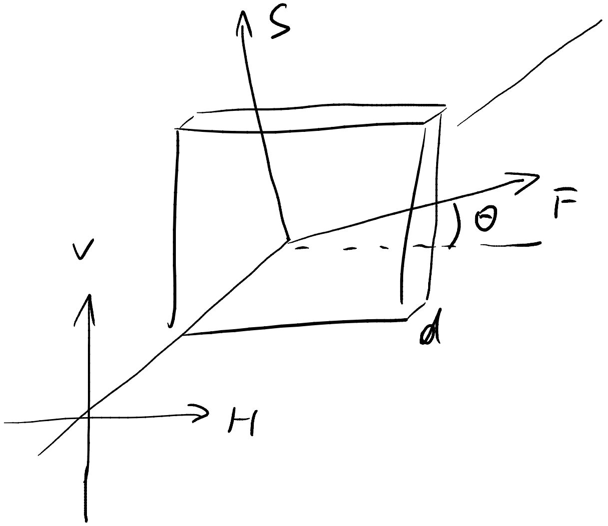
[Kok, 2010; KLM, Nature, 2001]

transmission probabilities: η1 = η3 ~ 85%; η2 ~ 17%

success probability: 25%
# of ancilla photons: 2

Wave plates

- birefringent material: polarisation-dependent wave velocity



- F: fast axis, parallel to optical axis
  S: slow axis, perpendicular to opt. axis
- phase shift

$$\phi_i = k_i d = \frac{c}{v_i} k d = n_i k d$$

n_i…refractive index (i=F,S)

$$n_S > n_F$$

- **half-wave plate:** π– phase shift between fast and slow component

$$\phi_S - \phi_F = \pi$$

$$n_S k d - n_F k d = \pi$$

$$d = \frac{\lambda}{2} \frac{1}{n_S - n_F}$$

Half-wave plate

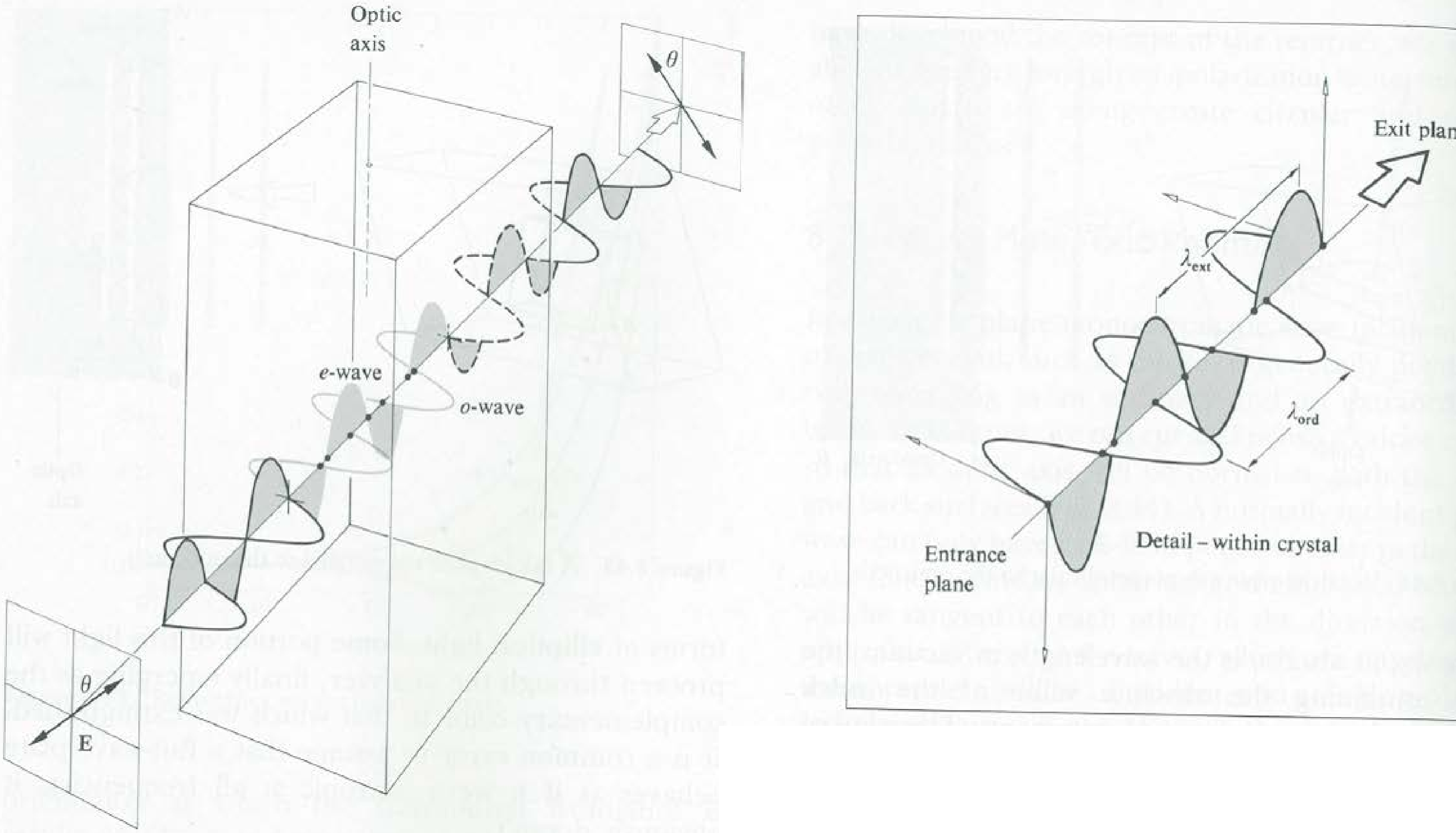


Figure 8.46 A half-wave plate.

Waveplates - Operations

half-wave plate:

$$|H\rangle \rightarrow \cos 2\theta |H\rangle - \sin 2\theta |V\rangle$$
$$|V\rangle \rightarrow \sin 2\theta |H\rangle + \cos 2\theta |V\rangle$$

$$U_{HWP}(\theta) = \begin{pmatrix} \cos 2\theta & -\sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

→π–rotation about **y-axis**

for θ=π/4: $$U_{HWP}(\pi/4) = U_Y = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$U_Y|V\rangle = |H\rangle$; $U_Y|H\rangle = |V\rangle$

quarter-wave plate: $$\phi_S - \phi_F = \pi/2, \qquad \theta = \pi/4$$

(linear -> circular)

$$U_{QWP}(\pi/4) = U_Z = e^{-i\pi/4} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$

→ π/2-rotation about z-**axis**

$$|L\rangle = \frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle) \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix}$$

$U_Z|L\rangle \propto (|H\rangle - |V\rangle)/\sqrt{2} = |A\rangle$

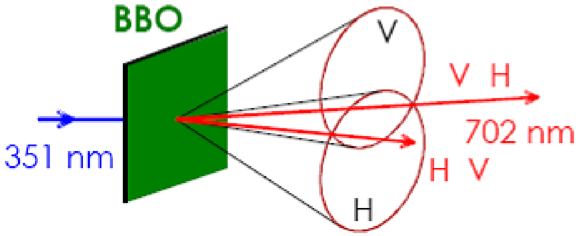
λ/2 and λ/4 wave plates are sufficient for QIP!

Entanglement creation - Parametric Down Conversion

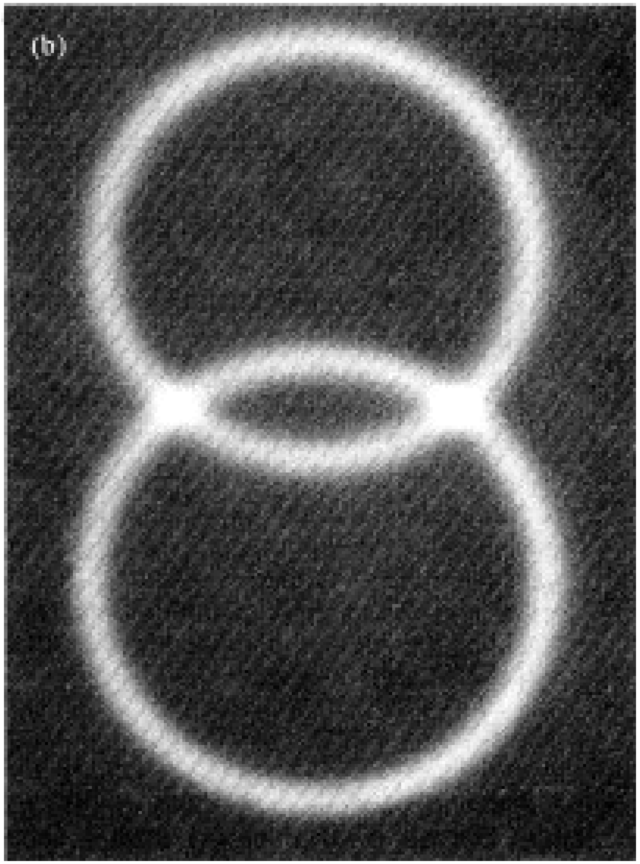
Generation of entangled photon pairs using nonlinear medium (BBO (beta barium borate) crystal)

parametric down-conversion

- 1 UV-photon ➔ 2 "red" photons
- conservation of
  energy $\omega_p = \omega_s + \omega_i$
  momentum $\vec{k}_p = \vec{k}_s + \vec{k}_i$
- Polarisationskorrelationen (typ II)



$$|\Psi^-\rangle = \tfrac{1}{\sqrt{2}}\left(|H\rangle|V\rangle - |V\rangle|H\rangle\right)$$



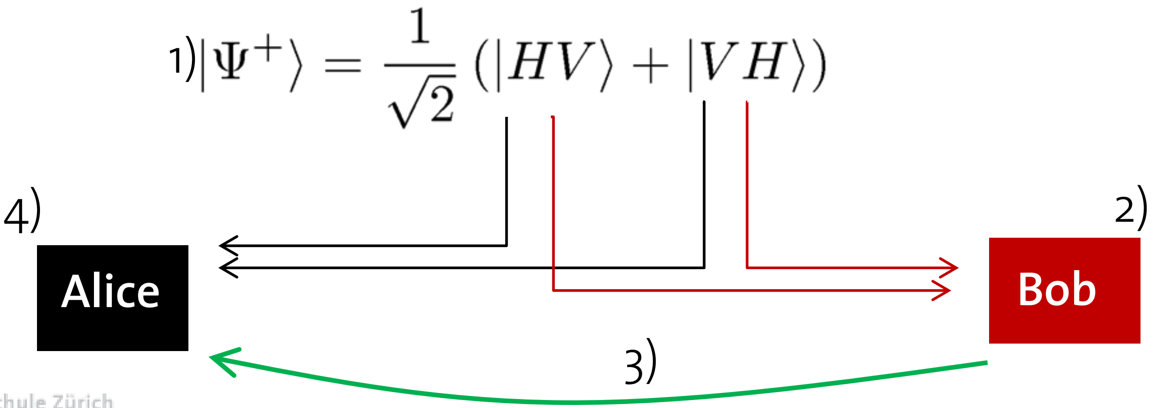
Kwiat et al., PRL 75 (1997).

Superdense Coding

task: Transmit two bits of classical information between Alice (A) and Bob (B) using only one qubit. Alice and Bob share an entangled qubit pair prepared ahead of time.

protocol:

1) Alice and Bob each have one qubit of an entangled pair
2) Bob does a quantum operation on his qubit depending on which 2 classical bits he wants to communicate
3) Bob sends his qubit to Alice
4) Alice does one measurement on the entangled pair



1)$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|HV\rangle + |VH\rangle)$

Superdense coding

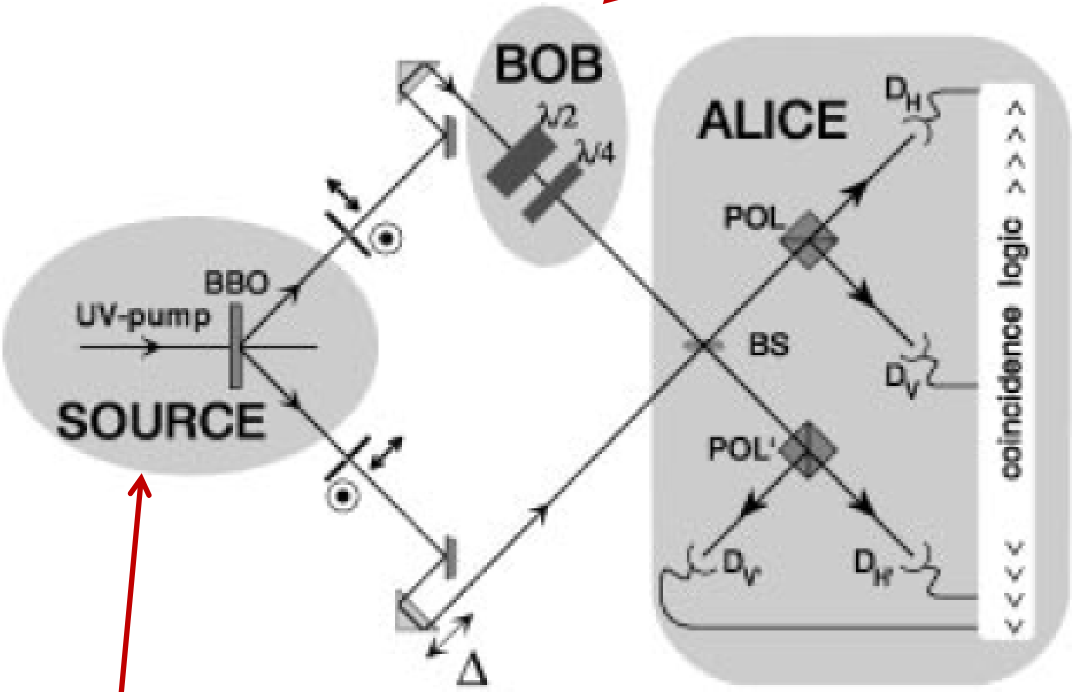
bit to be transferred	Bob's operation	resulting 2-qubit state (Bell states)	Alice's measurement
00	I_2	$I_2 \|\psi\rangle = (\|HV\rangle + \|VH\rangle)/\sqrt{2} = \|\Psi^+\rangle$	$\|\Psi^+\rangle$
01	Y_2 (HWP)	$Y_2 \|\psi\rangle = (\|HH\rangle + \|VV\rangle)/\sqrt{2} = \|\Phi^+\rangle$	$\|\Phi^+\rangle$
10	Z_2(QWP)	$Z_2 \|\psi\rangle = (\|HV\rangle - \|VH\rangle)/\sqrt{2} = \|\Psi^-\rangle$	$\|\Psi^-\rangle$
11	Y_2Z_2 (HWP + QWP)	$Y_2Z_2 \|\psi\rangle = (\|HH\rangle - \|VV\rangle)/\sqrt{2} = \|\Phi^-\rangle$	$\|\Phi^-\rangle$

- two qubits are involved in protocol BUT Bob only interacts with one and sends only one along his quantum communications channel
- two bits cannot be communicated sending a single classical bit along a classical communications channel

Bennett & Wiesner, Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states, Phys Rev Lett 60, 2881 (1992).

Realization of superdense coding

state manipulation

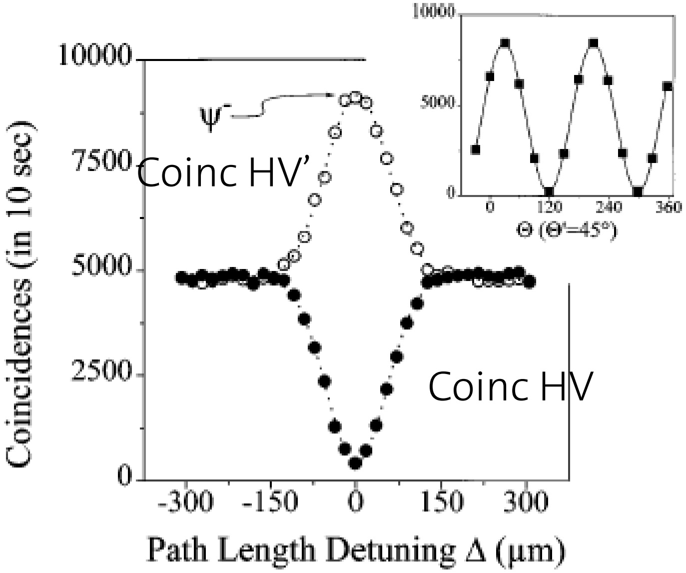


preparation of entangled pair

Bell state measurement

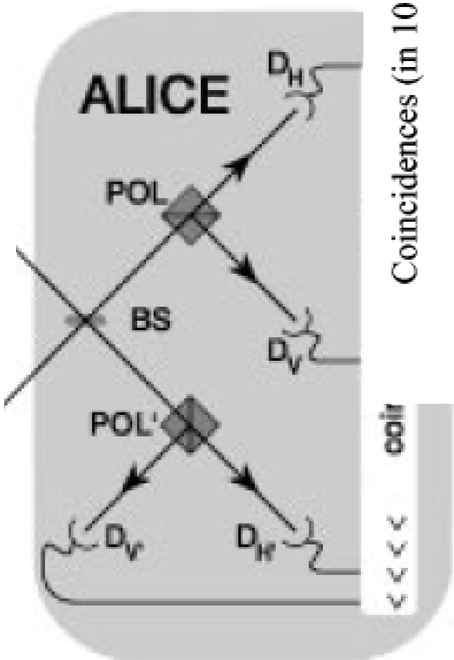
Mantle, Weinfurter, Kwiat, Zeilinger, PRL 76 (1996)

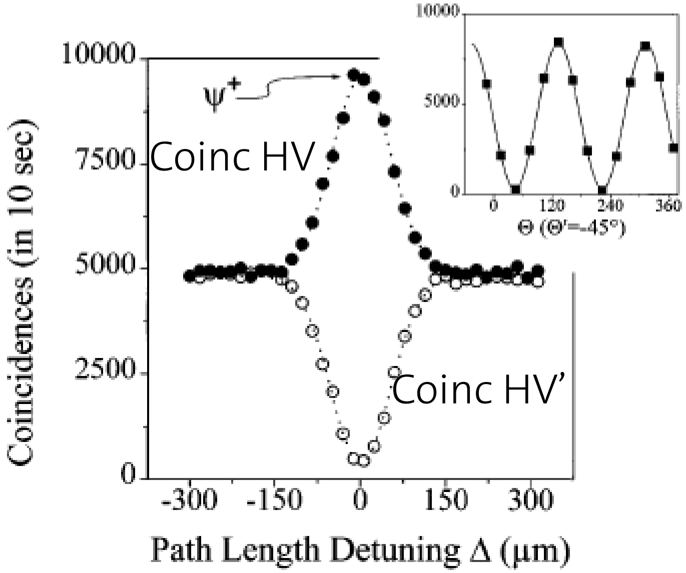
Realization of superdense coding



Coinc HV’

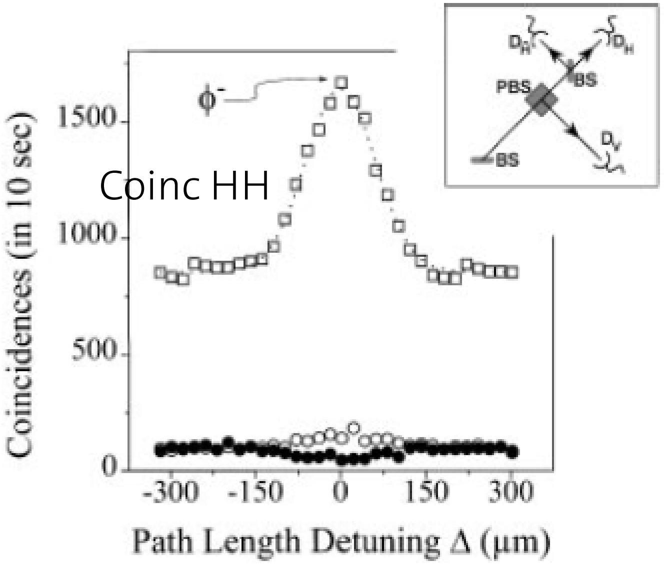
Coinc HV





Coinc HV

Coinc HV’

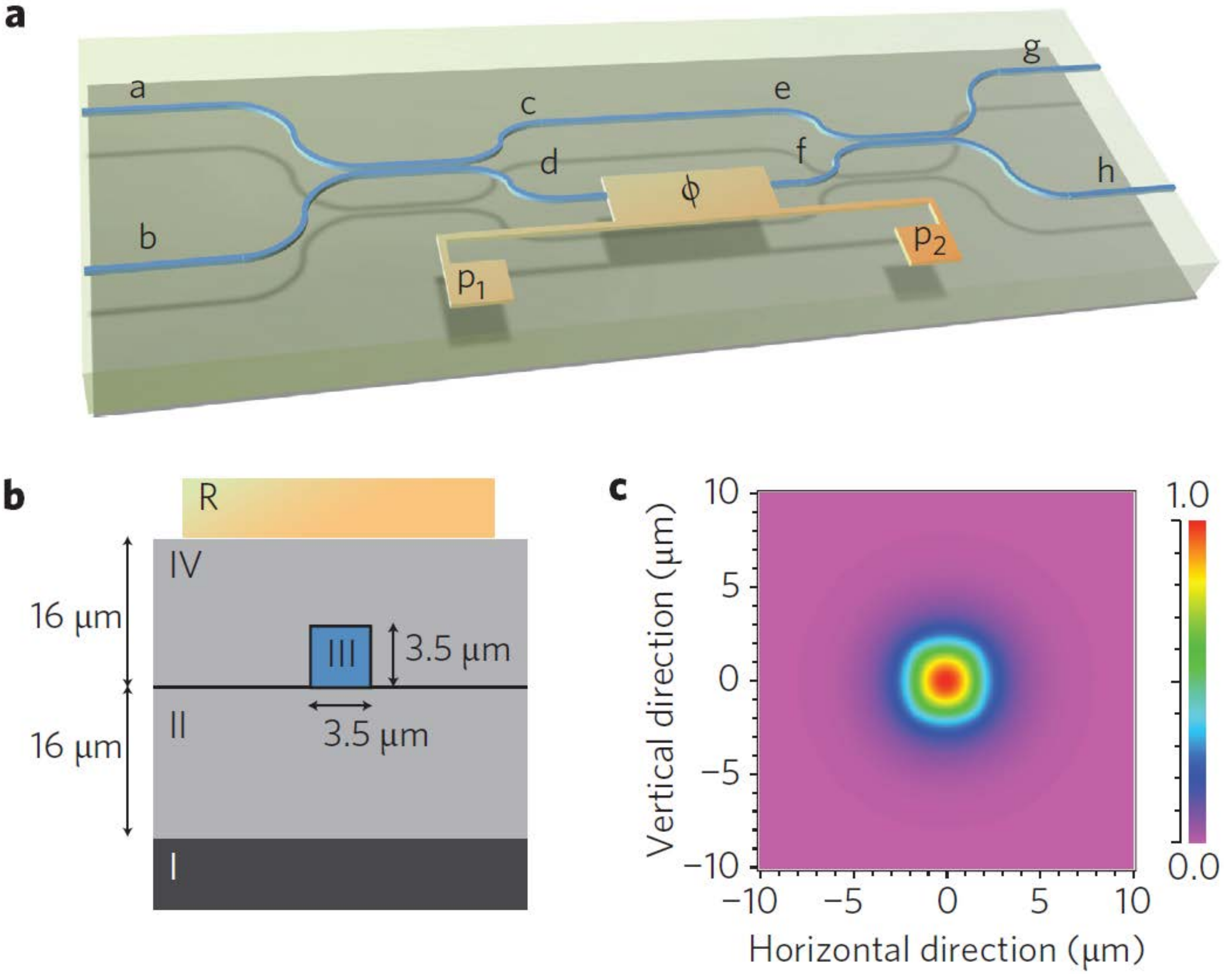


Coinc HH

Mantle, Weinfurter, Kwiat, Zeilinger, PRL 76 (1996)

Future perspectives: On-chip photonics

waveguides, beamsplitters and phase shifters on a chip



J. C. F. Matthews et al. Nat. Photonics 3, 346 (2009)