Single photons for quantum computation

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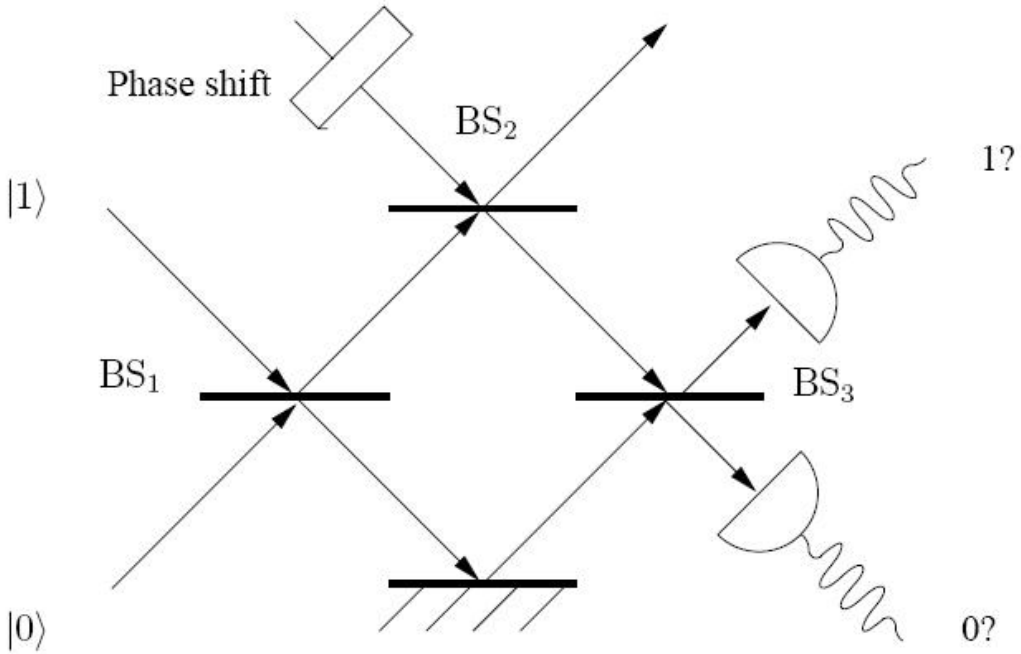
Quantum information processing and resources

- Within the program to build optical quantum computers efficient algorithms have been invented, e.g. in the important work of Knill, Laflamme and Milburn:
  A scheme for efficient quantum computation with linear optics, Nature **409**, 46-52 (2001).
- These schemes rely on Fock state $|1\rangle$ as a resource. So far there are no sources that can produce this Fock state with certainty.

Nonlinear phase shift as an example

A very basic unit in these schemes is the nonlinear phase shift.



Transformation by measurement

We want following transformation to take place:

$$\alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle - \gamma|2\rangle \tag{1}$$

This is only realized if the input states are exactly $|1\rangle$ and $|0\rangle$ and if the measurement results are 1 and 0 photons for the respective modes as well. In all other cases the transformation is different, including all sorts of unwanted effects (absorption). The probability to obtain the measurement results given perfect detectors is $\frac{1}{4}$.

What do we use the density operator for?

We prepare states $|\psi_i\rangle$ with corresponding probabilities p_i. Then we put this procedure in terms of the density operator ρ.

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| \tag{2}$$

Noisy photons

- Realistic single-photon sources are imperfect in the sense that they produce mixtures ρ of vacuum $|0\rangle$ and the single-photon Fock state $|1\rangle$.

$$\rho = p|1\rangle\langle 1| + (1-p)|0\rangle\langle 0| \tag{3}$$

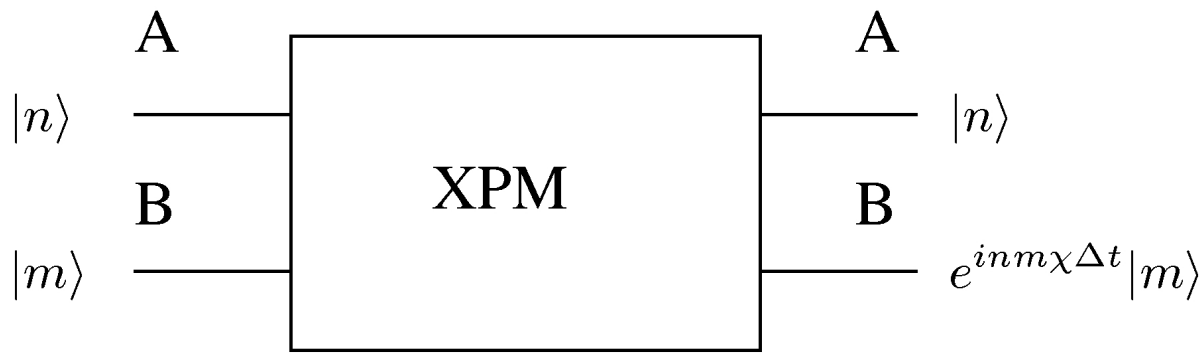
- We call p the efficiency of the source.
- The goal is to announce the single-photon Fock state when it is has been emitted by the source.

The action of cross phase modulation

Cross phase modulation (XPM) is described by the Hamiltonian

$$H = -\chi a^\dagger a\, b^\dagger b \tag{4}$$

χ is a function of the third order susceptibility $\chi^{(3)}$.

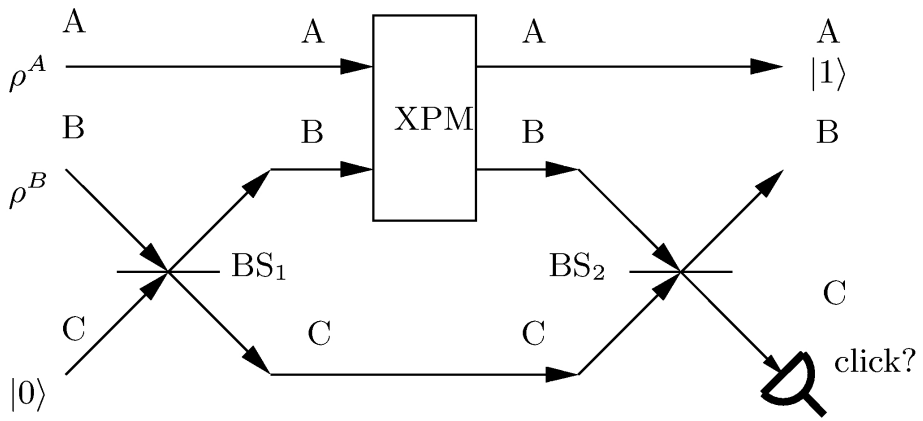


A two-mode Fock state $|m, n\rangle$ evolves in time Δt ($\hbar = 1$)

$$\exp(-iHt)|m, n\rangle = \exp(i\ \chi\Delta t\ m\, n)|m, n\rangle \tag{5}$$

Detection of a phase shift

- We use a Mach-Zehnder interferometer to detect the phase shift due to cross phase modulation between mode A and B.

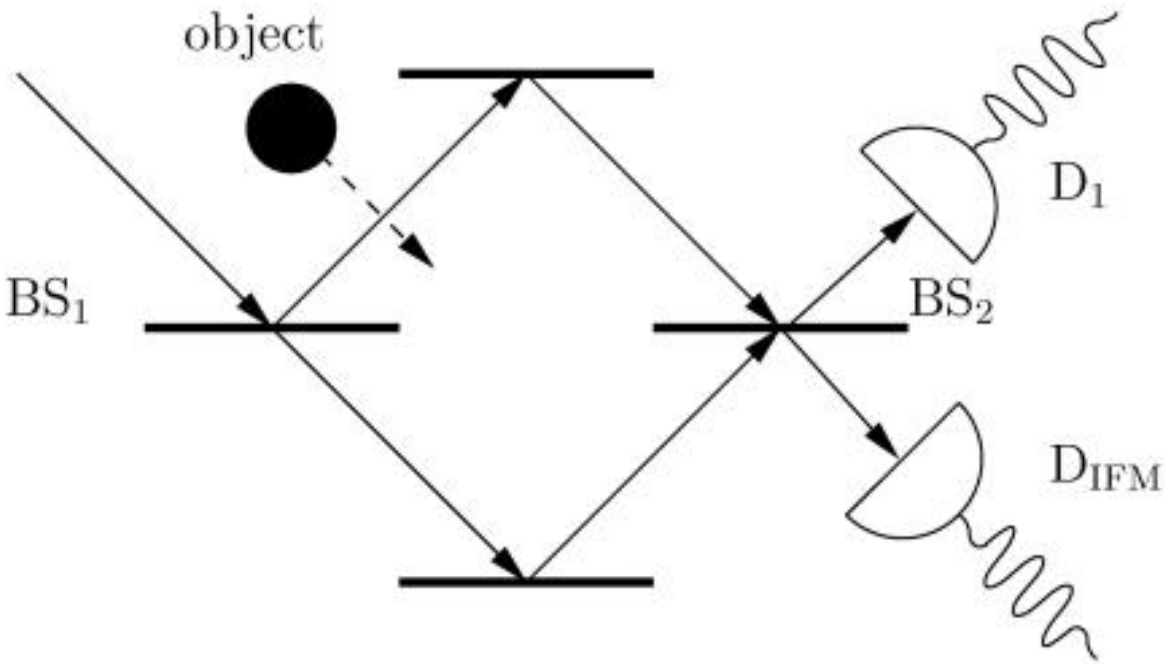


- Signal mode A contains the mixture we want to purify.
- Probe mode B is supposed to contain a coherent state.

- No photon in mode A – no phase shift – no detector click.
- A photon in mode A – phase shift - probability for detector click
- Detector click heralds the single-photon Fock state $|1\rangle$.
- If we use a coherent state $|\beta\rangle$ in mode B the probability for this event is given by

$$p(\text{click}|1^A) = 1 - \exp(-|\beta|^2 \sin^2(\tfrac{\chi \Delta t}{2})) \tag{6}$$

What is absorption good for?

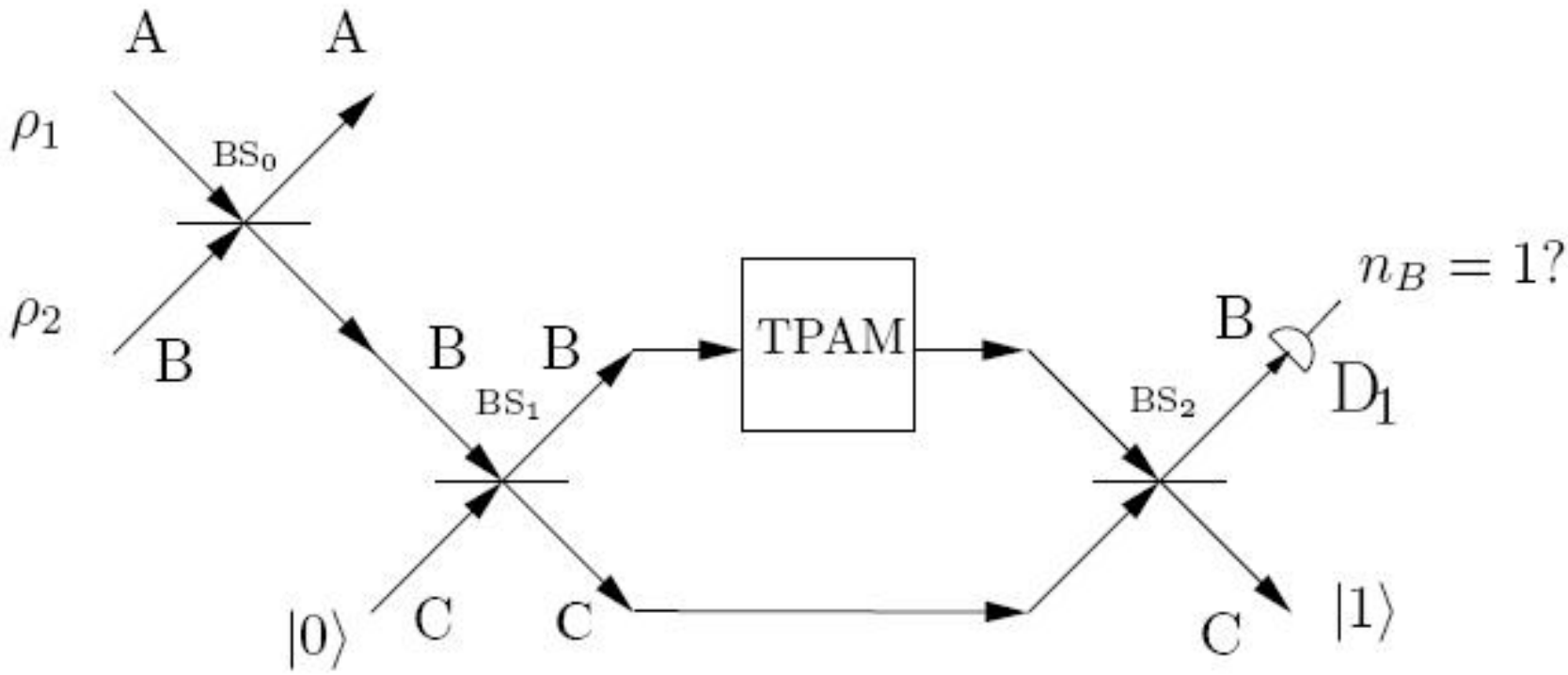


Transformation

$$
\begin{aligned}
|0\rangle|g\rangle &\xrightarrow{TPAM} |0\rangle|g\rangle \\
|1\rangle|g\rangle &\xrightarrow{TPAM} |1\rangle|g\rangle \\
|2\rangle|g\rangle &\xrightarrow{TPAM} \alpha|0\rangle|e\rangle + \beta|2\rangle|g\rangle \; . \qquad (7)
\end{aligned}
$$

TPAM means Two-photon absorbing medium

Heralding of photons using TPA



References

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- *Quantum non-demolition measurement of the photon number via the optical Kerr effect*, N. Imoto, H. A. Haus, Y. Yamamoto, Phys. Rev. A **32**, 4 (1985).
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