Quantum physics and the beam splitter mystery

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Plan of presentation

- **Part 1** Beamsplitter theoretical models
  - Quantum physics
  - Classical wave optics

- **Part 2** Beamsplitter experimental setups
  - Hanbury Brown and Twiss experiment
  - Mach-Zehnder interferometer

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Quantum view of the beamsplitter

- Macroscopic, "black-box" matrix model
  - Energy conservation

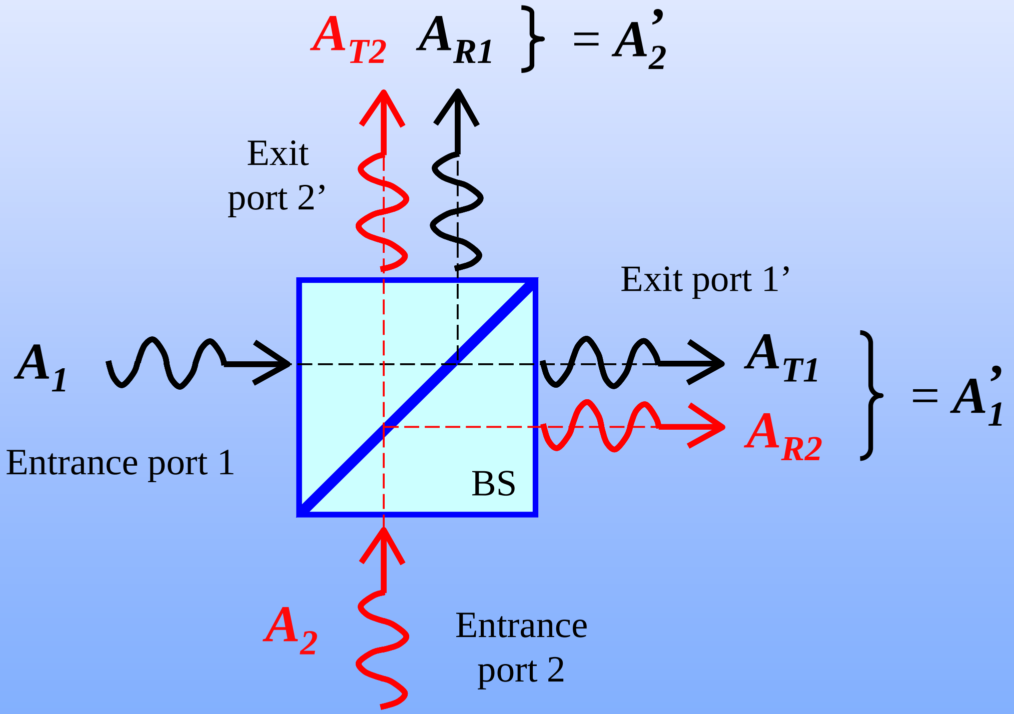
$$A'_1 A'^*_1 + A'_2 A'^*_2 = 1$$

  - Unitary operator (TBC)

$$A'_1 A'^*_2 + A'_2 A'^*_1 = 0$$

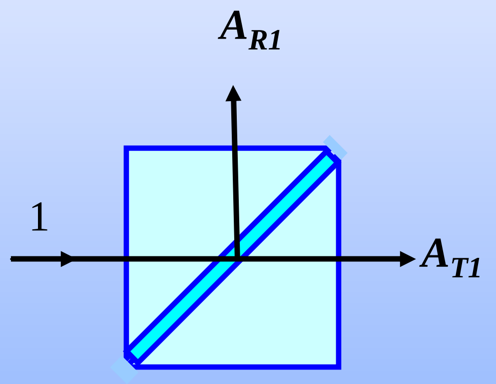
  - Beamsplitter matrix:

$$M_{\text{BS}} = \frac{1}{\sqrt{2}} \begin{bmatrix} i & 1 \\ 1 & i \end{bmatrix}$$



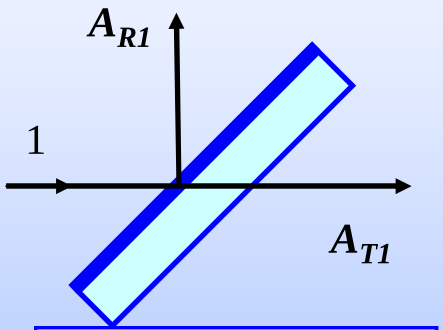
Real world beamsplitters

- Here are essentially studied "symmetric" beamsplitters

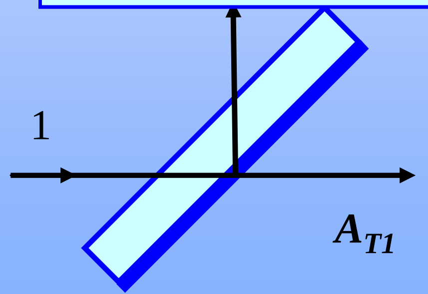


Cube beamsplitter

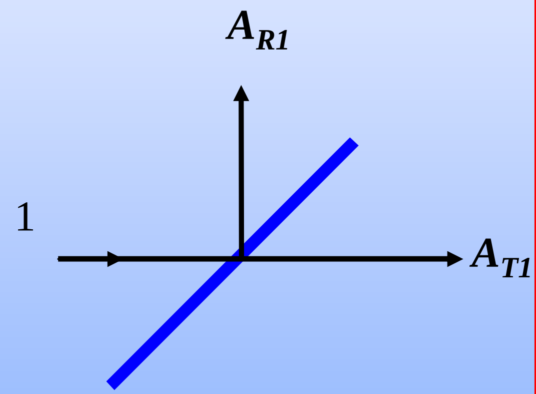
$$M_{BS} = \frac{1}{\sqrt{2}} \begin{bmatrix} i & 1 \\ 1 & i \end{bmatrix}$$



$$M_{BS} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$$



Asymmetric beamsplitters



Pellicle beamsplitter

$$M_{BS} = \frac{1}{\sqrt{2}} \begin{bmatrix} i & 1 \\ 1 & i \end{bmatrix}$$

Wave optics model of the beamsplitter

- **Multi-interference effect as in Fabry-Perot interferometers**

$$A_{T1} = \frac{t_{12} t_{21} \exp(i\varphi)}{1 - r_{21}^2 \exp(2i\varphi)}$$

$$A_{R1} = \frac{r_{12} + r_{21}(t_{12}t_{21} - r_{12}r_{21})\exp(2i\varphi)}{1 - r_{21}^2 \exp(2i\varphi)}$$

- **Lossless beamsplitter:**

$$A_{R1} = -r_{21} \frac{1 - \exp(2i\varphi)}{1 - r_{21}^2 \exp(2i\varphi)}$$

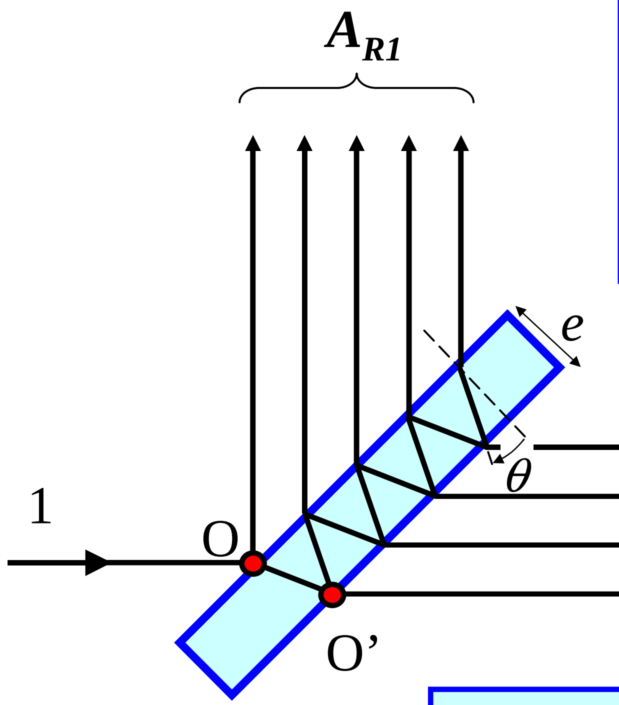
  - **Energy conservation**

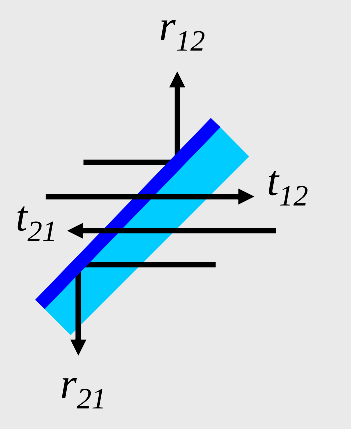
$$|A_{T1}|^2 + |A_{R1}|^2 = 1$$

  - **Achromatic phase-shift**

$$\phi_{R1} - \phi_{T1} = Arg\left[A_{R1} A_{T1}^*\right] = Arg\left[i \sin\varphi\right] = \pm\frac{\pi}{2}$$

Internal phase φ may depend on λ, θ...

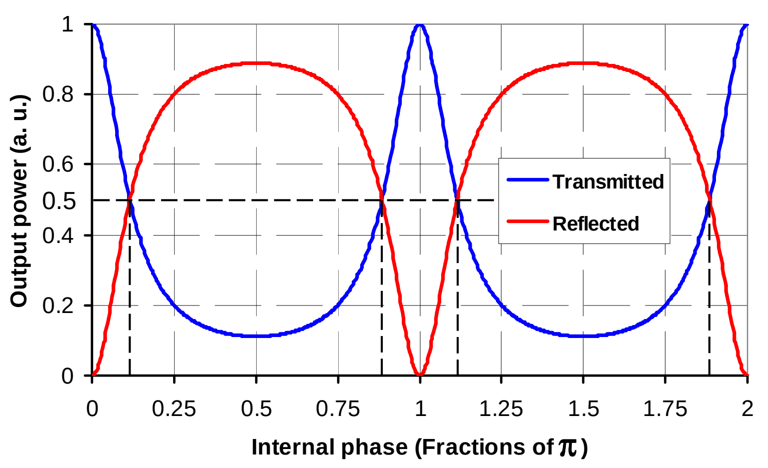


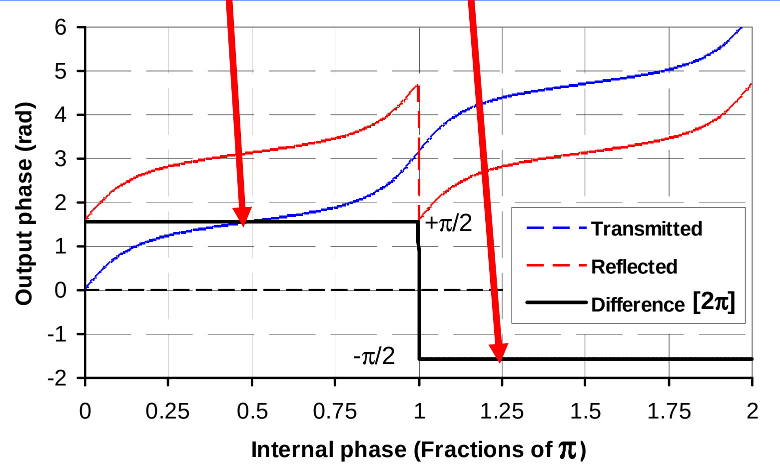


$$\varphi = k\, n e \cos\theta = \frac{2\pi}{\lambda} n e \cos\theta$$

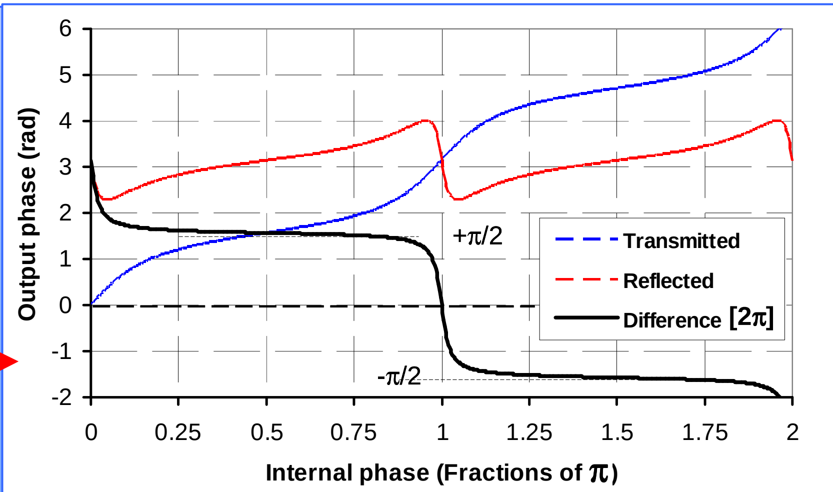
BS transmitted amplitudes and phase-shift

Lossless beamsplitter → Achromatic phase-shift of ±π/2



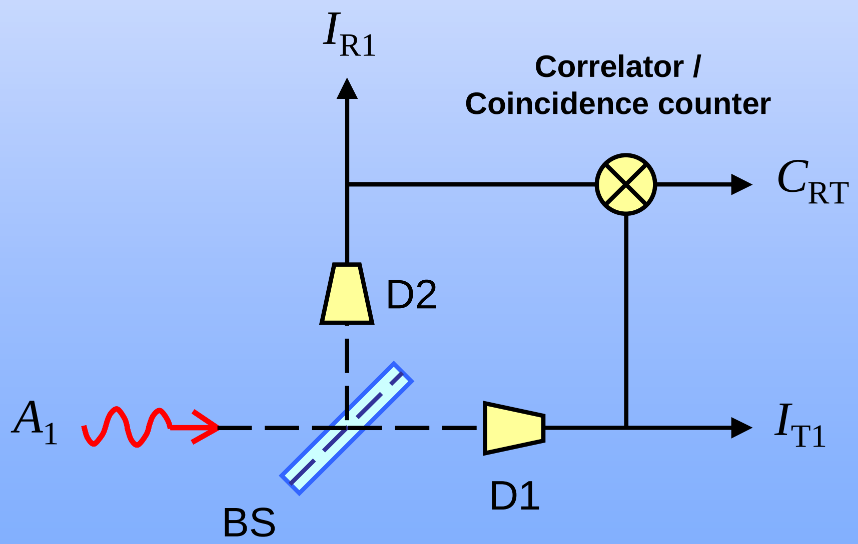


Absorbing beamsplitter

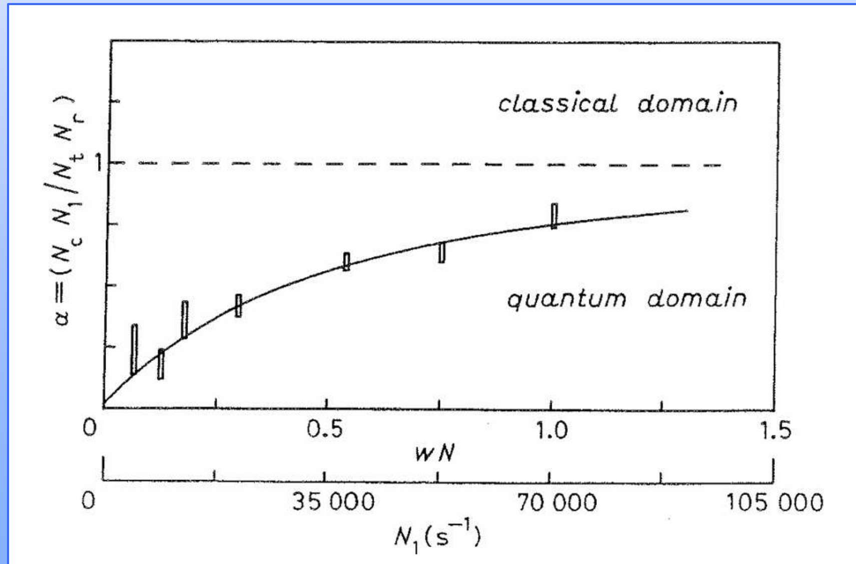


BS correlation experiments

- **Inspired from Hanbury Brown and Twiss experiment on intensity interferometry (1956)**
- **Used in coincidence counting mode by Grangier, Roger and Aspect (GRA) → Anti-correlation at low light levels (1986)**
- **Demonstrates the particle nature of light (indivisible photon)**



Measurement apparatus



Experimental results

GRA experiment – Classical model

- Uses classical notions of coherence length, generated currents…

Transmitted amplitude

$$A_{T1}(t,k)=\frac{1}{\sqrt{2}}\exp(-ikct)$$

π/2 phase shifted

Reflected amplitude

$$A_{R1}(t,k)=\frac{i}{\sqrt{2}}\exp(-ikct)$$

- First integration on spectral domain $[k-\delta k/2, k+\delta k/2]$

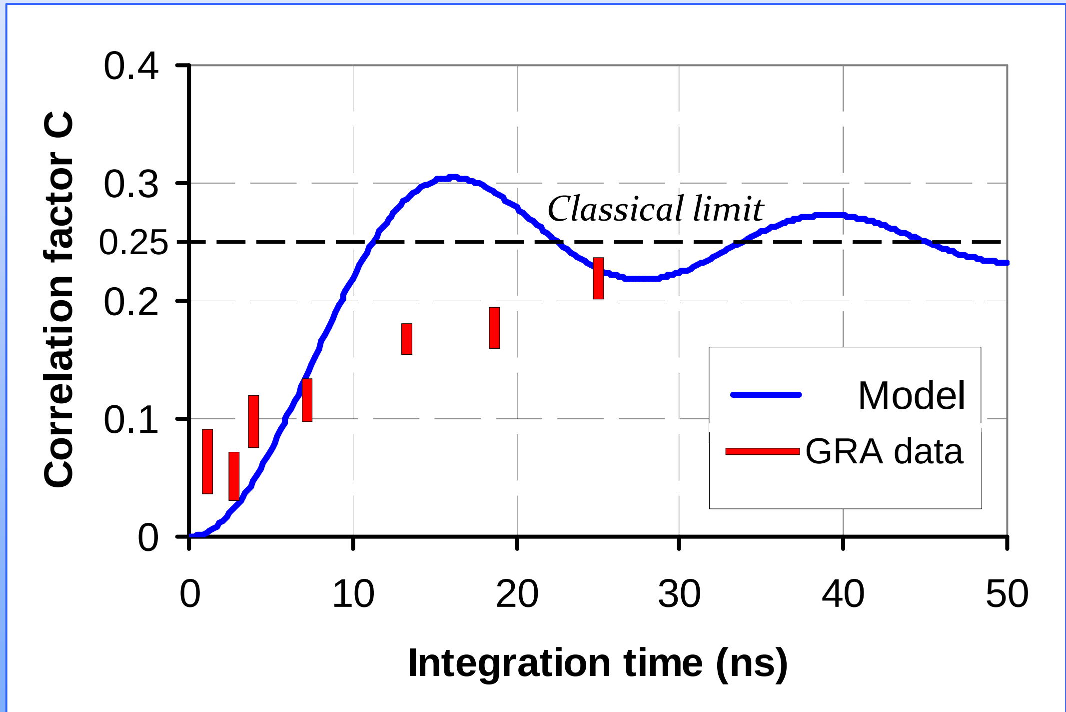
$$C_{RT}^{\delta k}(t)=\frac{1}{2\delta k}\int_{k-\delta k/2}^{k+\delta k/2} A_{T1}(t,k')A_{R1}(t,k')\,dk'=\frac{i}{2}\exp(-2ikct)\sin c(\delta kct)$$

- Second integration on time domain $[-\tau,+\tau]$

$$C_{RT}=\frac{1}{2\tau}\int_{-\tau}^{+\tau}\left[\mathrm{Re}\,al\left(C_{RT}^{\delta k}(t)\right)\right]^2 dt=\frac{1}{2\tau}\int_{-\tau}^{+\tau}\sin^2(2kct)\sin c^2(\delta kct)\,dt$$

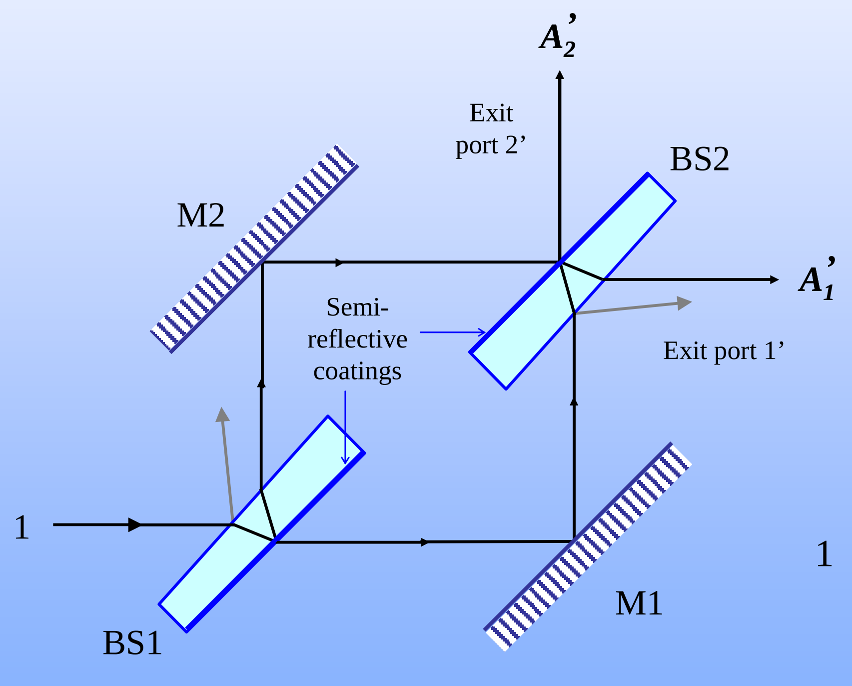
GRA experiment – Classical model

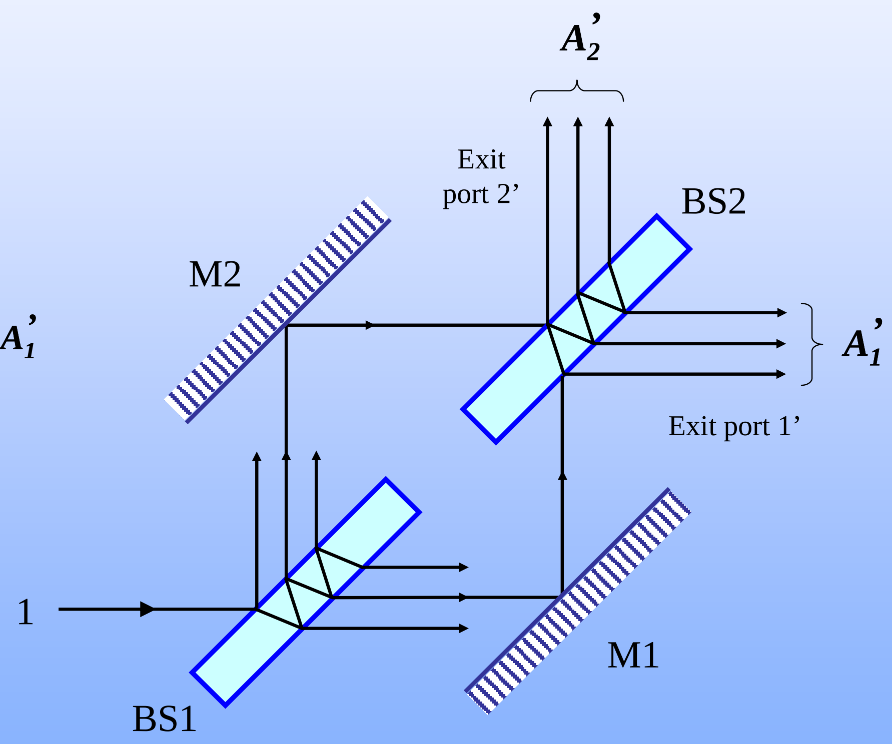
- Final expression $C_{RT} = \left(1 - \sin c\left(2kc\tau\right)\right)/4$
- Not in excellent agreement due to drastic approximations
- But accounts for experimental photon anti-correlation



The Mach-Zehnder interferometer

- Originally used as metrology tool in optics, gas dynamics etc.





Non symmetric, one reflexion only configuration

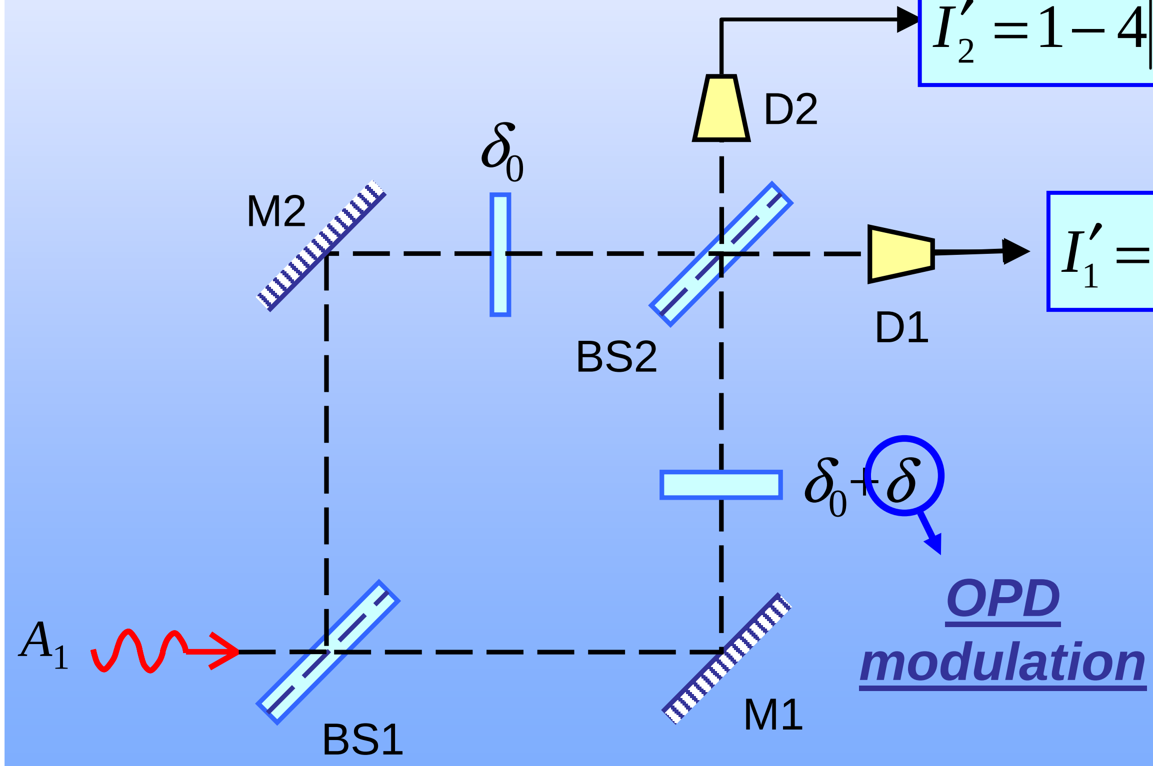
Symmetric configuration, double Fabry-Perot effect

MZ interferometer – OPD modulation δ

- Achromatic phase-shift $\Delta\phi = \pm\pi/2$ when $\delta = 0$
- Equal to 0 [π] otherwise

$$I_2' = 1 - 4\left|A_{T1}A_{R1}\right|^2 + 4\left|A_{T1}A_{R1}\right|^2 \sin^2\left(k\delta/2\right)$$

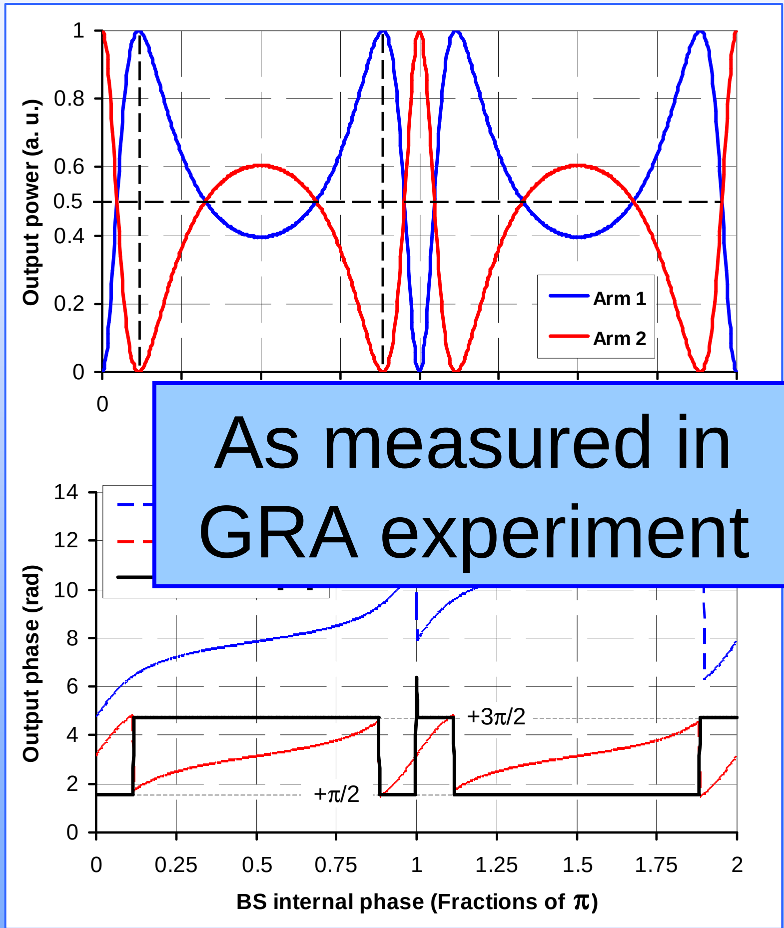
$$I_1' = 4\left|A_{T1}A_{R1}\right|^2 \cos^2\left(k\delta/2\right)$$



- Energy conservation OK
- In agreement with quantum optics

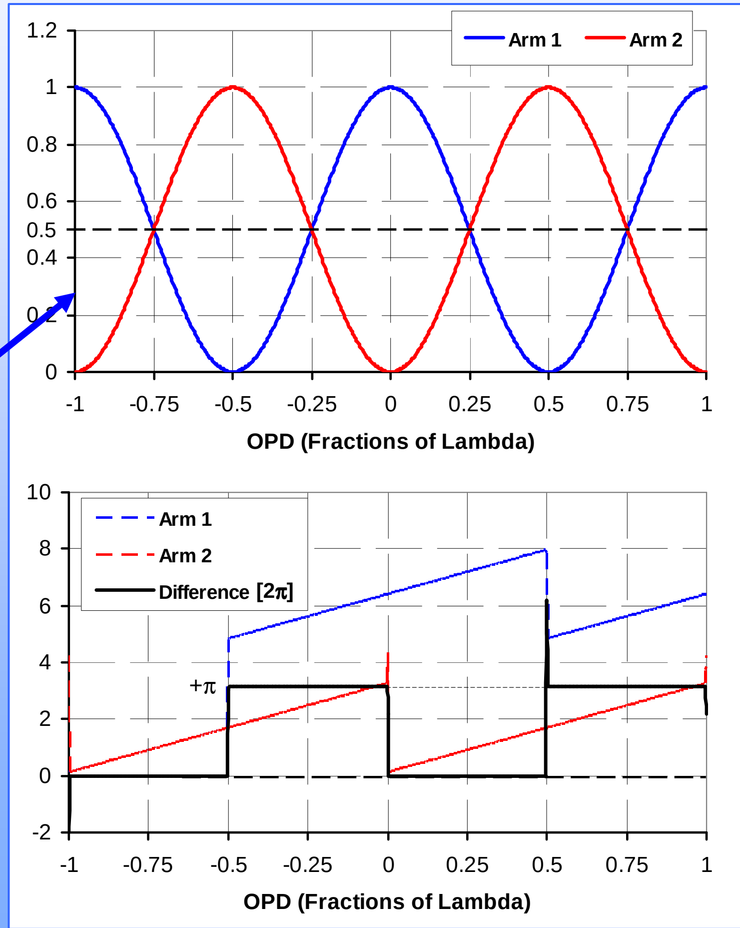
MZ interferometer – Wave optics model

At zero optical path difference



As measured in GRA experiment

With OPD modulation



Conclusion

- Quantum and wave optics BS theories are in global agreement. They both describe a **$\pm\pi/2$ phase shift** between transmitted/reflected electric fields
  - Quantum physics is a macroscopic "black-box" model
  - Classical optics evidences a multi-interference effect
- 4th-order interference (HBT) experiments show anti-correlation of BS outputs (GRA)
  - Quantum physics Interpretation → confirms photon existence
  - Can also be explained with classical wave optics model **including** the $\pm\pi/2$ phase shift
- Future work on other interference experiments
  - Mach-Zehnder, Hong-Ou-Mandel…