WAVE-PARTICLE DUALISM

lab course I/II
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Abstract

Light has both particle and wave character. Depending on the experiment only one property emerges. This lab course presents an apparatus, based on a Michelson interferometer, that illustrates both aspects and their coexistence. In the first part, you work on theoretical exercises and in the second part you realize different experiments with the experimental setup.

Contents

1 Overview

The following procedure is recommended:

1. Get familiar with the theoretical background of a Michelson interferometer, based on this lab instructions. If necessary, consult further literature. Solve the problems stated in the text.
2. Build the setup based on the instructions. Open a lab journal and document your work during the practical part.
3. Do the experiments concerning the wave character of light.
4. Do the experiments concerning the particle character of light.
5. Extend the setup with the quantum eraser.
6. Write a lab course report based on your lab journal.

2 Theoretical basis

This chapter includes a classical and quantum mechanical introduction of the theory of a Michelson interferometer. Further literature can be found in [1, 2, 3].

2.1 The electric field

This chapter introduces the electric field in its classical and quantized representation.

2.1.1 Classical description

The classical, scalar electric field in its complex analytical representation reads

$$E(\mathbf{r},t) = E^{+}(\mathbf{r},t) + E^{-}(\mathbf{r},t). \tag{1}$$

In order to motivate an analogy (see chapter 2.1.2) between the quantized radiation field and the harmonic oscillator, which you know from the quantum mechanics I lecture, we describe the electric field in a finite volume $\mathcal{V}$ with corresponding discrete mode expansion

$$E^{+}(\mathbf{r},t) = \frac{1}{2}\sum_{\mathbf{k}} E_{\mathbf{k}}^{+}\, \mathrm{e}^{i(\omega_{\mathbf{k}}t - \mathbf{kr})}, \qquad \left[E^{\pm}(\mathbf{r},t)\right]^{*} = E^{\mp}(\mathbf{r},t). \tag{2}$$

2.1.2 Quanutm mechanical description

In quantum electro dynamic is the electric field quantized.[1] In the framework of this theoretical introduction we limit ourself to the basic steps, that are necessary for the derivation of the photon annihilation and creation operator. The quantization is done by replacing the Fourier coefficients in eq. (2) by hermitian operators, i.e.

$$E_{\mathbf{k}}^{+} \longrightarrow \widehat{E}_{\mathbf{k}}^{+} = i\sqrt{\frac{\hbar\omega_{\mathbf{k}}}{2\varepsilon_0\mathcal{V}_Q}}\hat{a}_{\mathbf{k}}, \qquad E_{\mathbf{k}}^{-} \longrightarrow \hat{E}_{\mathbf{k}}^{-} = -i\sqrt{\frac{\hbar\omega_{\mathbf{k}}}{2\varepsilon_0\mathcal{V}_Q}}\hat{a}_{\mathbf{k}}^{\dagger} \tag{3}$$

with quantization volume $\mathcal{V}_Q$. The Fourier coefficients $\hat{a}_{\mathbf{k}}$ and $\hat{a}_{\mathbf{k}}^{\dagger}$ denote the photon annihilation and creation operators, thus annihilate or create a photon in mode $\mathbf{k}$

$$\hat{a}_{\mathbf{k}}|n_{\mathbf{k}}\rangle = \sqrt{n}|(n-1)_{\mathbf{k}}\rangle, \qquad \hat{a}_{\mathbf{k}}^{\dagger}|n_{\mathbf{k}}\rangle = \sqrt{n+1}|(n+1)_{\mathbf{k}}\rangle, \qquad n \in \mathbb{N}. \tag{4}$$

One claims that $\hat{a}_{\mathbf{k}}|0\rangle = 0$, where $|0\rangle$ denotes the vacuum state. The operators fulfil the commutation relations

$$[\hat{a}_{\mathbf{k}}, \hat{a}_{\mathbf{k}'}^{\dagger}] = \delta_{\mathbf{kk}'}^{(3)}, \quad [\hat{a}_{\mathbf{k}}, \hat{a}_{\mathbf{k}}] = [\hat{a}_{\mathbf{k}}^{\dagger}, \hat{a}_{\mathbf{k}}^{\dagger}] = 0, \tag{5}$$

where $\delta_{\mathbf{kk}'}^{(3)}$ is the Delta Dirac function in three dimensions. From the quantum mechanics lecture, you know the description of *one* harmonic oscillator by raising and lowering operators $\hat{a}$ and $\hat{a}^{\dagger}$. They excite the system in discrete energy levels. The quantized electric field can

[1] The quantization of the electric field is discussed explicitly in [4].

be interpreted as $(\mathbf{r}, t)$-depending superposition of infinite many harmonic oscillators, where each mode $\mathbf{k}$ is assigned to *one* harmonic oscillator. The energy of such an oscillator is given by the number of quanta (photons) in the corresponding mode. Because photons are bosons, a mode $\mathbf{k}$ can be populated by an arbitrary number of photons. Equivalently, a harmonic oscillator can be excited to an arbitrary energy level.

2.2 Theory of a beamsplitter cube

The starting point of the theoretical and experimental understanding of a Michelson interferometer is the beamsplitter cube. Its classical and quantum mechanical physics is discussed in the following subsections.

2.2.1 The scattering matrix

Generally, a beamsplitter has two input and two output ports (E1, E2) and (A1, A2). The reflection and transmissionn properties of an optical layer system are fully described by the scattering matrix of S-matrix. Its general form reads

$$\mathbf{S} = \begin{pmatrix} t' & r \\ r' & t \end{pmatrix} = \begin{pmatrix} |t'|\, e^{i\phi_{t'}} & |r|\, e^{i\phi_r} \\ |r'|\, e^{i\phi_{r'}} & |t|\, e^{i\phi_t} \end{pmatrix}, \qquad \mathbf{S} \in \mathbb{C}, \tag{6}$$

where (r, t) are the reflection and transmission coefficients for the input port E1, and (r', t') the corresponding coefficients for input E2 of the transmitting medium [2] (fig. 1 and fig. 2).

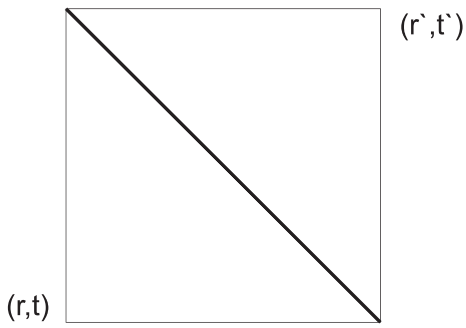

FIGURE 1: Schematic of a beamsplitter cube with reflection and transmission coefficients (r, t) and (r', t').

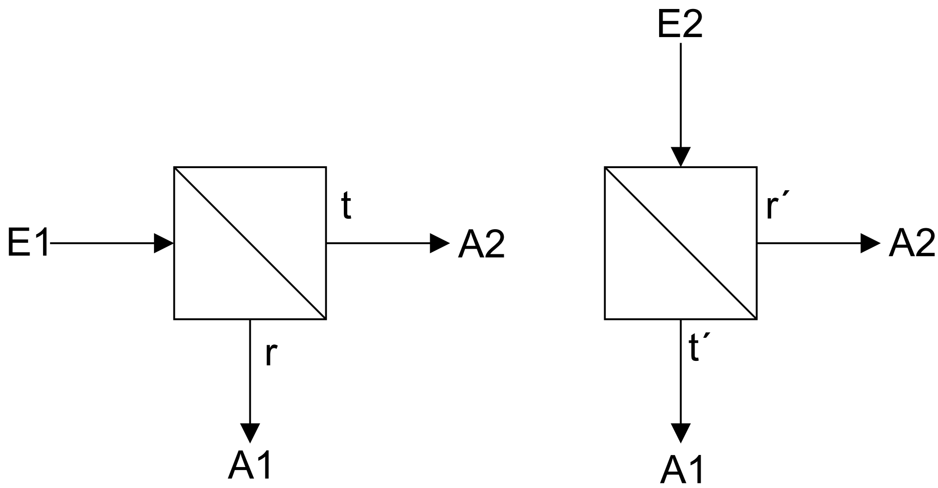

Figure 2: Schematics of a beamsplitter cube with input ports (E1, E2) and output ports (A1, A2).

Energy conservation requires in a lossless medium [3]

$$|r'| = |r|, \quad |t'| = |t|, \quad |r|^2 + |t|^2 = 1, \quad r^* t' + r' t^* = 0. \tag{7}$$

According to [5] the phases in eq. (6) for a bemasplitter cube are chosen

$$\phi_r = \phi_t = \phi_{r'} = 0, \quad \phi_{t'} = \pi. \tag{8}$$

For a 50%/50% beamsplitter cube, it follows that the reflection and transmission coefficients are

$$r = t = r' = \frac{1}{\sqrt{2}}, \quad t' = \frac{1}{\sqrt{2}} e^{i\pi} = -\frac{1}{\sqrt{2}}. \tag{9}$$

2.2.2 Classical description

At position $z = 0$, the laser emits the electric field $\mathbf{E_0}(\mathbf{r}, t)$ in the form of a linear polarized, monochromatic plane wave, that propagates along the z-direction, i.e.

$$E_0(z, t) = E_0 e^{i(\omega_0 t - k_z z)}. \tag{10}$$

For simplicity, we use the notation $E_{0,j}(z, t) \rightarrow E_0(z, t)$, $j \in \{x, y\}$. After the distance z_0, we place a beamsplitter cube with coefficients (r, t).

Exercise 1: Derive eq. (10) out of the general solution

$$\mathbf{E_0}(\mathbf{r}, t) = \frac{1}{(2\pi)^4} \int d^3k' \int d\omega \; \mathbf{E_0}(\mathbf{k}', \omega) \mathrm{e}^{i(\omega t - \mathbf{k}'\mathbf{r})} \tag{11}$$

of the wave equation in vacuum. We assume $\mathbf{E_0}(\mathbf{k}', \omega) = f(\mathbf{k}')\mathbf{g}(\omega)$.

Considering eq. (6) and only one input beam, the output fields $E_1(z_0,t)$ und $E_2(z_0,t)$ are given by (fig. 3)

$$\begin{pmatrix} E_1(z_0,t) \\ E_2(z_0,t) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ E_0(z_0,t) \end{pmatrix} = \frac{E_0}{\sqrt{2}} e^{i(\omega_0 t - k_z z_0)} \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \tag{12}$$

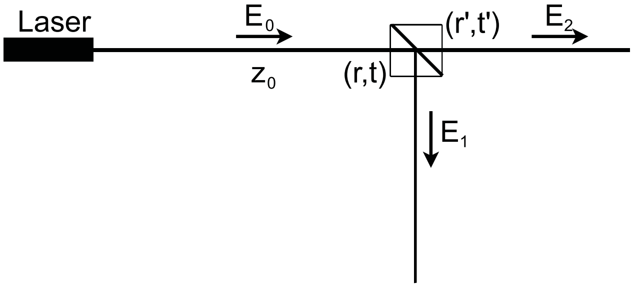

FIGURE 3: Schematic of a beamsplitter cube with classical input and output fields $E_0(z_0,t)$, $E_1(z_0,t)$, and $E_2(z_0,t)$.

2.2.3 Quantum mechanical description

Analogically to the classical description, we consider only photons that propagate in z-direction, i.e. $\mathbf{k} \to k_z$. We replace the mode index k_z by i, because we deal only with monochromatic photons in mode $k_z = \frac{2\pi}{\lambda}$ in interferometer arm i. Then, the relations in eq. (5) read

$$[\hat{a}_i, \hat{a}_j^\dagger] = \delta_{ij}, \quad [\hat{a}_i, \hat{a}_j] = [\hat{a}_i^\dagger, \hat{a}_j^\dagger] = 0, \quad i,j \in \{0,1,2\}. \tag{13}$$

One is tempted to set $\hat{a}_1$ and $\hat{a}_2$ (equivalently to the classical description) to

$$\hat{a}_1 = r\hat{a}_0 \qquad \hat{a}_2 = t\hat{a}_0 \tag{14}$$

It is easy to show that for general r and t the operators in eq. (14) violate eq. (13). Thus, lead to an incorrect quantum mechanical description of a beamsplitter cube. The correct quantum mechanical description requires an additional input port $\hat{a}_3$ (fig. 4), although in the experiment no photon is sent through it. Quantum mechanically this absence is associated to an incoming vacuum state $|0\rangle$. The beamsplitter transforms the incoming annihilation operators $\hat{a}_0$ and $\hat{a}_3$ by left multiplication with the S-matrix [eq. (6)]. Using the resulting relation

$$\begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix} = \begin{pmatrix} t' & r \\ r' & t \end{pmatrix} \begin{pmatrix} \hat{a}_3 \\ \hat{a}_0 \end{pmatrix} \tag{15}$$

and eq. (9), we end up finally with

$$\hat{a}_1 = \frac{1}{\sqrt{2}}(\hat{a}_0 - \hat{a}_3), \quad \hat{a}_2 = \frac{1}{\sqrt{2}}(\hat{a}_0 + \hat{a}_3). \tag{16}$$

Exercise 2 (facultative): Show for general r and t, that the operators in eq. (16) satisfy the commutation relations in eq. (13) (now with $i, j \in \{0, 1, 2, 3\}$) under the conditions

$$|r'| = |r|, \quad |t'| = |t|, \quad |r|^2 + |t|^2 = 1, \quad r^* t + r' t'^* = 0. \tag{17}$$

Now, they lead to a correct quantum mechanical description of a beamsplitter cube.

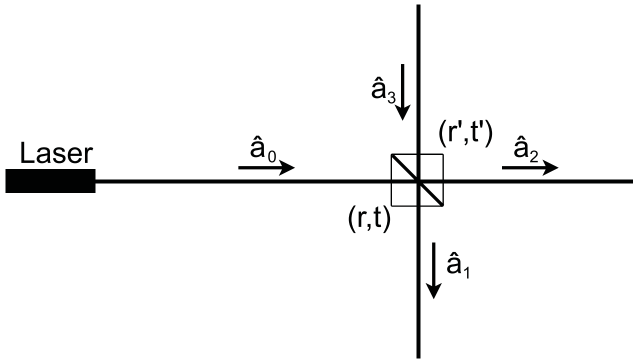

FIGURE 4: Schematic of a beamsplitter cube with the photon operators $\hat{a}_i$, $i \in \{0, 1, 2, 3\}$.

2.3 Theory of a Michelson interferometer

The Michelson interferometer is completed by the two mirrors M1 and M2 according to fig. 5.

2.3.1 Calssical description

The electric fields in eq. (12) propagate through free space from the beamsplitter cube to the mirrors M1 and M2 and back again. They become

$$\begin{aligned} E_1(z_0 + z_1, t) &= \frac{E_0}{\sqrt{2}} e^{i(\omega_0 t - k_z(z_0 + z_1))}, \\ E_2(z_0 + z_2, t) &= \frac{E_0}{\sqrt{2}} e^{i(\omega_0 t - k_z(z_0 + z_2))}. \end{aligned} \tag{18}$$

After antoher transmission and reflection, respectively at the beamsplitter and propagation z_3, the electric field reaches the detector in a superposition of fields $E_1'(z_0 + z_1 + z_3, t)$ and $E_2'(z_0 + z_2 + z_3, t)$, thus lead to

$$\begin{aligned} E_3(z_0 + z_3, z_1, z_2, t) &= E_1'(z_0 + z_1 + z_3, t) + E_2'(z_0 + z_2 + z_3, t) \\ &= \frac{E_0}{2} e^{i(\omega_0 t - k_z(z_0 + z_1 + z_3))} + \frac{E_0}{2} e^{i(\omega_0 t - k_z(z_0 + z_2 + z_3))} \\ &= \frac{E_0}{2} e^{i(\omega_0 t - k_z(z_0 + z_3))} (e^{-ik_z z_1} + e^{-ik_z z_2}). \end{aligned} \tag{19}$$

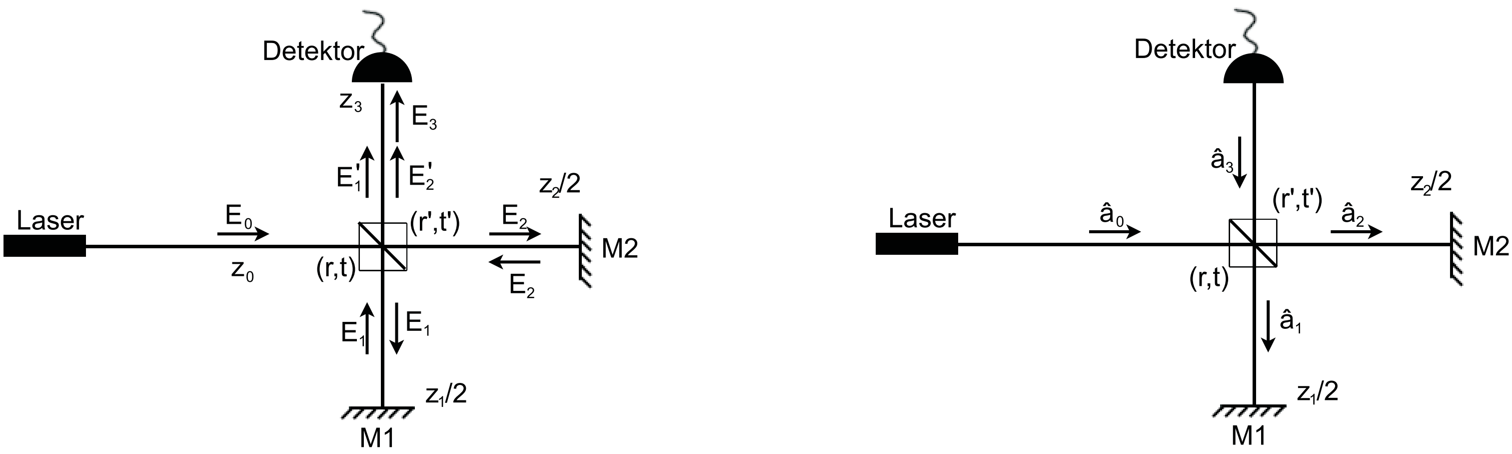

FIGURE 5: Schematics of a Michelson interferometer. Left: classically, right: quantum meachanically

Exercise 3: Show that the intensity at the detector is given by

$$I(z_1, z_2) = \frac{\epsilon_0 c}{2} |E_0|^2 \cos^2 \left[\frac{k_z(z_2 - z_1)}{2} \right]. \tag{20}$$

For certain arm length z_1, at a fixed arm length $z_2 = z_{20}$ and $k_z = \frac{2\pi}{\lambda}$, we get constructive or destructive interference.

Exercise 4: What happens with the intensity $I(z_1, z_2)$, if one interferometer arm is blocked? This question can be answered by means of eq. (19).

2.3.2 Quantum mechanical description

If we consider the free propagation and the following transmission and reflection at the beam-splitter, we get the field operator $\hat{d}$ at the detector output of the interferometer using eq. (16)

$$\begin{aligned} \hat{d} &= \hat{a}_1 e^{-ik_z z_1} t + \hat{a}_2 e^{-ik_z z_2} r' \\ &= \frac{1}{2}[\hat{a}_0(e^{-ik_z z_1} + e^{-ik_z z_2}) + \hat{a}_3(e^{-ik_z z_2} - e^{-ik_z z_1})]. \end{aligned} \tag{21}$$

In our experiment, the quantum mechanical photon count distribution

$$P_m(T) = \text{Trace}\left\{\hat{\rho}\hat{N}\frac{(\xi\hat{d}^\dagger\hat{d})^m}{m!}e^{-\xi\hat{d}^\dagger\hat{d}}\right\} \tag{22}$$

can be calculated with $\hat{d}$ in eq. (21) [6]. It is the probability to detect m photons during the measurement time T. The density operator $\hat{\rho}$ describes the photon statistic of the incoming light field. The normal operator $\hat{N}$ arranges all operator products such that all creation operators are on the left side (regardless the corresponding commutation relation). The quantum efficiency ξ describes the probability of detecting an incoming photon during measurement time T. A longer calculation ends up with a Bernoulli distribution

$$\begin{aligned} P_m(z_1, z_2, T) &= \sum_{n=m}^{\infty} P_n \binom{n}{m} \left\{\xi\cos^2\left[\frac{k_z(z_2 - z_1)}{2}\right]\right\}^m \\ &\quad \times \left\{1 - \xi\cos^2\left[\frac{k_z(z_2 - z_1)}{2}\right]\right\}^{n-m}. \end{aligned} \tag{23}$$

This expression is interpreted as the probability to detect m photons out of n incoming photons. P_n is the probability distribution, that n photons in mode k are emitted during the measurement time T. The cosine square has the arm difference as an argument and weights the probability of detecting a photon. For a monochromatic laser P_n follows a Poisson distribution

$$P_n = \frac{\bar{n}^n}{n!}e^{-\bar{n}}, \tag{24}$$

where $\bar{n}$ is the mean photon number.

Exercise 5: Show that

$$P_m(z_1, z_2, T) = \frac{(p\bar{n})^m}{m!}e^{-\bar{n}p} \tag{25}$$

using eq. (23), P_n of eq. (24), and the definition $p \doteq \xi\cos^2\left[\frac{k_z(z_2-z_1)}{2}\right]$.

In the classic limes, the standard deviation becomes zero for infinite number of measurements of m photons.

Exercise 6: Show that the expectation value $\bar{m}$ with $P_m(z_1, z_2, T)$ in eq. (25) is given by

$$\bar{m} = \bar{n}\xi\cos^2\left[\frac{k_z(z_2 - z_1)}{2}\right]. \tag{26}$$

Equation (26) represents the expectation value of detecting $\bar{m}$ photons on average during the measurement time T. If we assume a detector area A, then $\bar{m}$ corresponds to the classic limes. Thus, according to [3], the classic intensity equation (20) reads

$$I(z_1, z_2) = \frac{\bar{m}\hbar\omega}{AT}. \tag{27}$$

2.3.3 Michelson interferometer with tilted mirrors

If we slightly tilt mirror M1 (fig. 6), the propagation direction of one beam changes, and reaches the screen under the angle $\beta \neq 0$ with respect to the other beam. Because of this, interference fringes arises. Based on fig. 6, it is easy to derive

$$d = \frac{\lambda}{\sin(\beta)} \overset{\beta \ll 1}{\approx} \frac{\lambda}{\beta}, \tag{28}$$

where d denotes the distance between two intensity maxima and λ is the wavelength (distance between two successively following phase fronts).

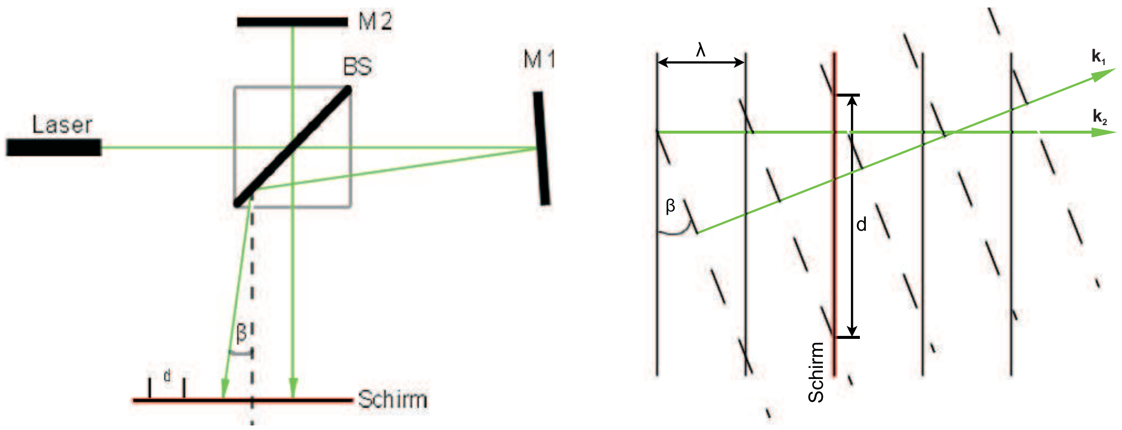

Figure 6: Left: schematic of a Michelson interferometer with tilted mirror M1. Right: tilted wave fronts reaching a screen. The superposition leads to interference fringes.

With fig. 6, it is easy to see, what happens if one arm length is changed. The phase front of the tilted beam moves along the wavevector $\mathbf{k_2}$, and therefore the intersection on the screen lies on another position. The number of fringes m, that can be seen when tilting the mirror, depends on the path difference Δs (fig. 7).

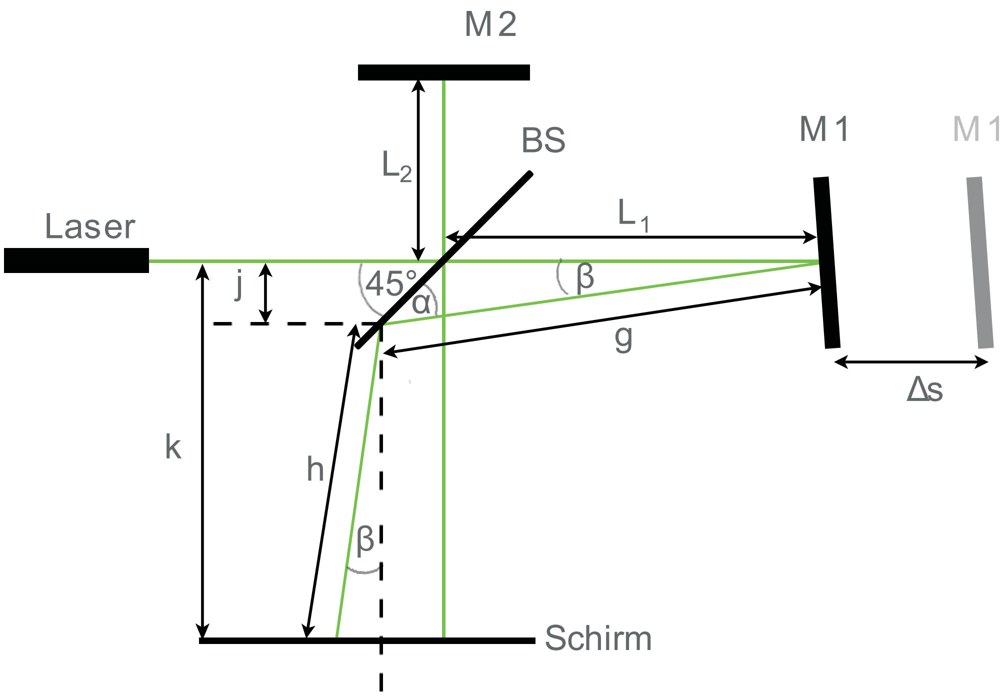

Figure 7: Schematic of a Michelson interferometer with tilted mirror. The laser beam reaches the beamsplitter under 45°. The mirror (M1) can be shifted by Δs.

exercisee 7: Show that m is given by

$$m = \frac{\Delta L}{\lambda} \overset{\beta \ll 1}{\approx} \frac{2 \cdot \Delta s}{\lambda}, \tag{29}$$

where λ is the wavelength, and β is the tilting angle. Calculate the length difference ΔL of the laser beam, that is caused by a piezo actuator change of Δs. The tilting angle of M1 is β. Use for the calculation the quantities $L_1(\Delta s)$, $g(\Delta s, \beta)$, $j(\Delta s, \beta)$, $h(\Delta s, \beta)$, and fig. 7.

3 Experimental setup

The basic idea of the setup is the following. Two beams are sent into a Michelson interferometer in order to show simultaneously experiments, that illustrate the wave and particle character of light. One beam is attenuated by a filter, and detected by a photomultiplier (PM). The other arrives (not attenuated) to a photodiode (PD). The PD measures the classical intensity I [eq. (20)]. The PM measures $\bar{m}$ of eq. (26). This chapter explains shortly each component of the setup by means of a legend, depicted in fig. 8.

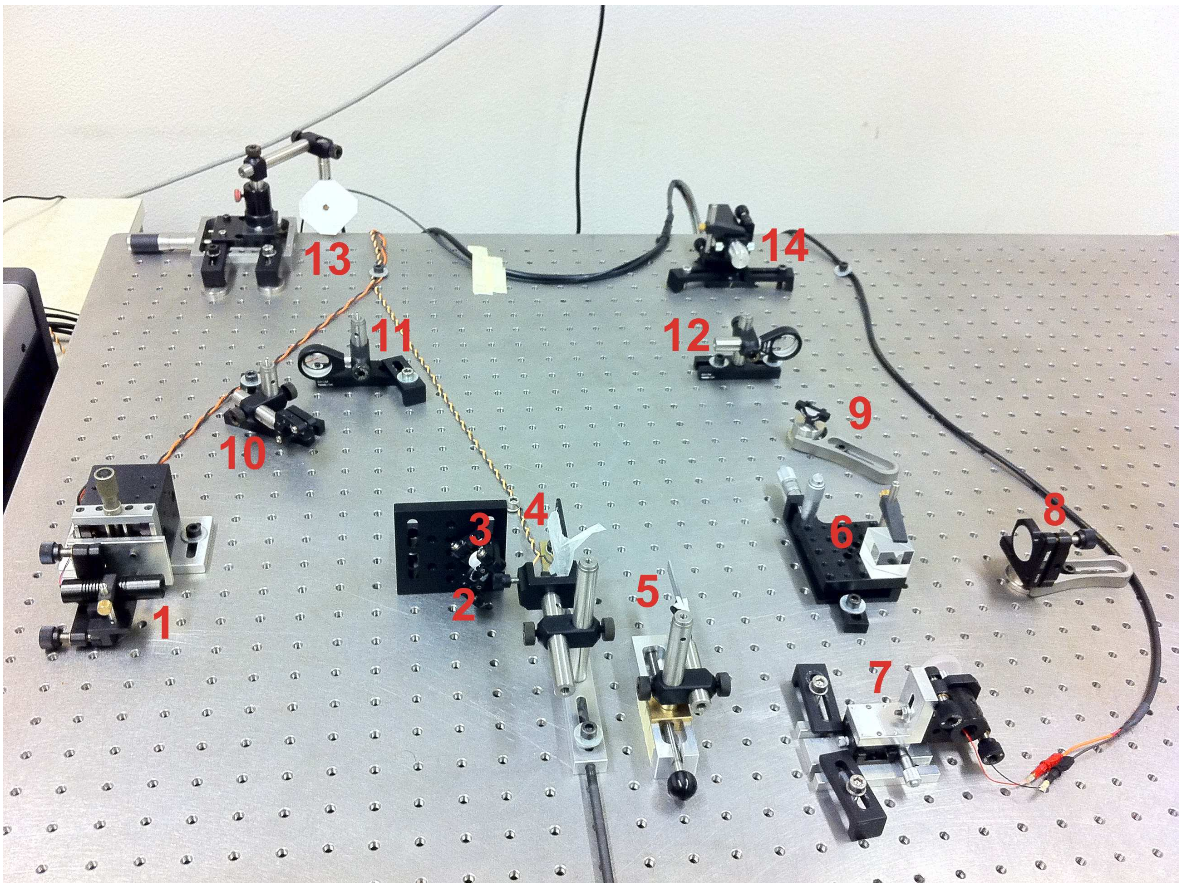

Figure 8: Photography of the experimental setup.

As a light source, we use a laser (1) at 532 nm wavelength. A beamsplitter BS1 (2) prepares two partial beams. A mirror M0 (3) reflects the reflected beam coming from BS1 parallel to the transmitted one. BS1 and M0 together build a lower beam A and a upper beam B. Beam B can be attenuated by a block filter (4) and a variable filter (5) (the variable filter is not used at this stage of the lab course). The position of the block filter switches an interlock. If the beam block is in the beam path, the PM (14) is enabled. If not, the interlock disconnects the power supply for the PM, thus protects it against high light intensities. The mount for the variable filter allows a stepless attenuation of beam B.

Both beams A and B pass through the Michelson interferometer. It consists of a beamsplitter cube BS2 on a pitch and yaw platform (6) and two tiltable mirrors M1 (7) and M2 (8). The mirror M1 is mounted on a piezo actuator, in order to change the path length of one arm of the interferometer. A rough positioning can be achieved by a translation stage. The stage can be locked by a setscrew on the side of the stage.

A D-mirror (9), placed at the output of the interferometer, picks out beam A, and another mirror M3 (10) reflects the beam parallel to beam B. Each beam is flared by a diffuser lens (11) and (12).

The PD (13) detects beam A and the PM (14) detects beam B. The signals are acquired by an electronic box. It is not only for signal acquisition and processing, but also used as power supply for the laser, pizeo actuator, and PM. As data acquisition, we use a DSO (digital storage oscilloscope), two loudspeakers, and a LabView VI ("Praktikum_Welle_Teilchen_Dualismus.vi"), that is used as a counter.

3.1 Elektronic box

The electronic box operates the experiment. The front panel is depicted schematically in fig. 9. Here the panel is shortly described, according to the manual [7].

Five optically separated elements controls the experimental setup.

Laser A switch starts the laser. A potentiometer sets the voltage for the laser. The setting is digitally displayed in units of volts. The maximum voltage is 3.19 volts. The laser operates at 3 volts (see introduction in chapter 5). Note that the laser need about 15 minutes to stabilize its power.

Photomultiplier If the interlock circuit is closed, the PM can be started by a switch. The control voltage for the high-voltage of the PM is tuned by the "HV level" potentiometer. This voltage is proportional to the high-voltage.

The "discr. level" potentiometer allows to set a threshold. If the incoming signal overcomes this threshold level, a TTL signal is generated and the LED "photon" flashes. The loudspeaker signal and the TTL signal are identical.

Piezo control The piezo actuator is used in one of five settings

- Position "remote": An external voltage (plugged at the "manual remote" input) is applied.
- Position "manual": A constant voltage is applied. It can be setted with the "man. level" potentiometer.
- Position "ramp": A triangle voltage of 15 $\pm$ "scan amplitude"/2 Volt is applied. It is defined by the "scan ampl." potentiometer.

- Position “lock”: An internal voltage is generated for the stabilizing mode. The “lock” function is discussed in chapter 5.2.1 in more detail.
- Position “open”: A constant voltage of 15 Volts is applied.

Fringe Lock The electronic includes a PI controller, that is used for stabilizing the interference fringes. The time constant of the integration can be set with the potentiometer I. If the integrator reached its maximum voltage, it can be reset with the corresponding button. The proportional part is set with the potentiometer P.

Photodiode A constant voltage can be added to the photodiode signal with the “PD offset” potentiometer. “PD gain” amplifies the signal. Note that this potentiometer is connected incorrectly, thus the scale has to be inverted (zero correspond to ten units).

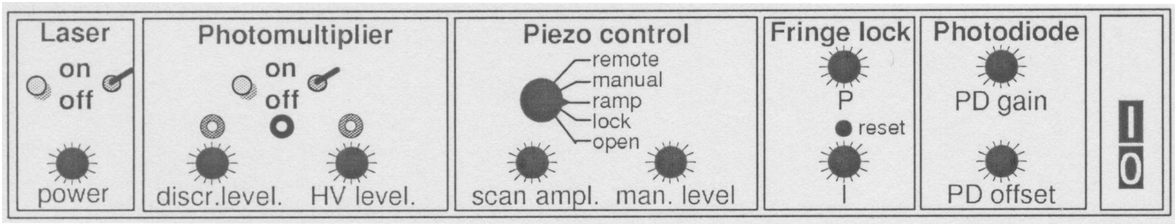

Figure 9: Schematic of the electronic box’ front panel (reference: [7]).

4 Alignment of the Michelson interferometer

Note: Before you start, the lab course assistent should give you a short instruction about laser safety.

This chapter is a guide for aligning the experimental setup, explicitly the Michelson interferometer. The labels and numbers correspond to chapter 3 and fig. 8, respectively. The elements (1)-(4) are prealigned, i.e. beam A has the same height as the D-mirror (9), and points parallel to a hole line. Beam B is aligned parallel to beam A. Moreover, the beamsplitter cube is mounted on the pitch and yaw platform. The block filter (4) should only attenuate beam B, and switches the interlock if it is placed in the beam path.

1. Arrange all components (1)-(12) temporary to get an overview. Both arms of the interferomter should have about the same length ($\approx$ 9 cm). The positions are marked on the lab table as aid.

2. Place an iris diaphragm directly after the block filter (4) on the height of beam A. Align mirror M2 (8) with blocked beam B (use the block filter) such that the reflected beam passes backwards through the diaphragm to the laser. The beam passes now parallel to the normal of the mirror.

3. Beam A and B should be parallel to each other, because BS1 (2) and M0 (3) are prealigned. Check this again by looking at beam B. Tilt M0 till the reflection goes back to the laser too. This is achieved by observing the beam at the laser output aperture.

4. Place the beamsplitter cube of the interferometer BS2 (6) in the lower beam A (block beam B) and rotate the platform such that two surface normals are oriented parallel to the beam. The generated partial beams propagates to M2 and to M1 (temporary set in step 1). Block the beam that goes to M2 and rotate the cube such that the back reflection in the cube propagates back to the diaphragm of step 2.

5. Fix and align mirror M1 (7) in such a way, that the two partial beam overlap on a screen at the output of the interferometer. Now you should see an interference pattern because of the interfaces of the beamsplitter cube BS2, even if you block the mirrors M1 and M2 (turn off the ambient light!). This interference disturb the experiments. Therefore rotate (do not pitch, otherwise the beam height changes) the platform a bit to prevent the superposition of two interference pattern.

6. Separate beam A and B with the D-mirror. Afterwards parallelize them again roughly with mirror M3 (10). To ensure perpendicular hitting of the detector, use a iris diaphragm to keep the beam height.

7. Use lense (11) and (12) to flare the interference pattern of beam A and B, respectively. To prevent aberration, the beam goes through the center of the lense, and its back reflection passes through a iris diaphragm.

8. For further attenuation of beam B, the variable filter (5) can be placed after the block filter (4). The reflection of both filters should pass backwards through the iris diaphragm of step 2 to the laser.

9. The PD (13) (detection area 8 mm^2) is mounted on a translation stage and fixed in maximal distance to the lense in the center of the beam A. This distance ensures that the detector resolves an intensity minimum even with multiple fringes, and does not detect light of a following maximum.

   Note: If necessary, let you explain the basics of the DSO.

   Fix the PM at the same distance without translation stage in beam B. The attachment in front of the detector is a sequence of diaphragms and filters. It prevents incidence of ambient light. To get a PM signal, you have to observe the DSO signal and activate the interlock by placing the block filter in the beam path. The PM operates only if the switch is pressed. This safety mechanism prevents the detector of overexposure. Chose the setting "ramp" for the piezo voltage, three volts for the laser voltage, and seven units (0.7 volts) for the PM volatge. Align the PM such that the DSO shows not only noise but typical photomultiplier signals. They raise strongly and then decrease exponentially. Optimize the PM orientation horizontally and vertically in order to get maximal spikes on the DSO. At the same time, you can audibly optimize the signal strength by means of the loudspeakers and check the count rate with LabView ("Praktikum_Welle_Teilchen_Dualismus.vi").

5 Experiments

The laser operates at a voltage of three volts. This guarantees the maximum difference between intensity maxima and minima in the interference pattern. The following experiments are done without the variable filter (5).

5.1 Wave character of light

5.1.1 Characterization of the interference pattern

Goal: After aligning the interferometer, you have to characterize the interference pattern.

Procedure: If the mirror, mounted on the piezo actuator, is tilted, you observe interference fringes. *Document what happens if you tilt the mirror increasingly. Discuss the result in the context of eq. (28) and eq. (29).*

5.1.2 Photodiode signal

Goal: Measure locally the intensity with the photodiode in order to get a detailed analysis of the interference fringes. The photodiode gives you a voltage proportional to the intensity of the incoming light. This voltage is displayed on the DSO.

Procedure: Tilt the mirror on the piezo actuator such that three vertical fringes arise. The experiment works with another number of fringes too, as long as the detector can resolve maximum and minimum. Operate the piezo in the "‘ramp"’ mode and the set the "‘scan amplitude"’ to maximum. *Record the photodiode signal one time with open interferometer arms and one time with one arm blocked. Check that the detector does not saturate. Save the signal with the DSO and analyze them with an suitable software, i.e. plot the signals depending on the piezo voltage. Try to get a signal as harmonic as possible.* Hint: Trigger to the ramp pattern of the piezo voltage to stabilize the PD signal. This is possible, because the both signals are correlated. At the backside of the electronic box, you find the piezo voltage that can be connected to the DSO. *Discuss possible causes why the PD signal is not perfectly harmonic. Check experimentally the result of exercise 4.*

5.2 Particle character of light

5.2.1 “Photons interfere only with itself”

Goal: Paul Dirac wrote in 1927 in his work “The Principle of Quantum Mechanics” [8]: “Each photon interferes only with itself.”. This should be shown with the following experiment.

Procedure: Despite the low held construction, the interference pattern is very sensitive to external influences. *Characterize the different external disturbances that influence the interference.* To compensate for disturbances, the electronic box has a build in stabilizing mode “lock mode”. This mode locks the interference fringes such that the PD always measures the same intensity. As soon as the electronics recognize a difference in the light intensity, the pizeo voltage is adjusted. The change of the piezo voltage leads to a change of the piezo position. Therefore the phase difference between the interfering partial beams changes, thus the intensity at the PD. Finally the PD measures the newly set intensity. If you scan the photodiode transversally through the interference fringes, the PM scans it simultaneously. The PM remains fixed.

Block the piezo mirror. The interference disappears. Accordingly, only one partial beam reaches the photomultiplier. Place the block filter in the upper beam path. This attenuates the beam hitting the PM and activates the interlock switch. Now, the PM can be operated. Start with a bias of seven units (0.7 volts). If the PM detects a photon, it generates a output signal that enters the electronic box. If the signal overcomes the threshold (discriminator level), a TTL signal is generated. This separates noise and the signal triggered by the photons. The TTL signal is rendered audible by the loudspeakers and can be recorded with the counter (LabView: "Praktikum_Welle_Teilchen_Dualismus.vi"). Alternatively, the detection rate of the PM can be recorded by means of the TTL signals fed into the DSO. Connect the TTL output of the electronic box with the DSO for this. Now, the signals can be plotted for an appropriate time period, stored, and counted with an suitable software of your choice. *State qualitatively what happens with the detection rate of the PM, if you change the high voltage and the threshold level by means of the acoustic signal. Moreover, state qualitatively the changes when looking at the LabView counter and/or your stored TTL signals.* Attention: Do not operate the PM with a high-voltage more than 8 units (0.8 volts). For the experiments with the PM, a threshold value of about 2.5 - 3 units is established.

Now lock the interference pattern with appropriate settings of the voltage and threshold level according to the following instructions:

1. Tilt the mirror M1 (7), till you see three fringes.

2. By means of the "offset" voltage, set the photodiode signal symmetrically around the central abscissa on the DSO (piezo mode "ramp").

3. Now, chose piezo mode "manual" and "man. level" such that the photodiode signal lies symmetrically around the central x-axis. With these settings the photodiode is placed exactly between an intensity maximum and a minimum, and the electronics knows how to correct the piezo voltage when a intensity change arise.

4. Next, the piezo mode is set to "lock". If the stabilization works correctly, the signal stays around the central x-axis, even if you push gently on the lab table. If you observe oscillations of the PD signal, reduce the gain of the signal with the "gain" potentiometer.

5. If all is set correctly, the photodiode can be move slowly (!) by means of the translation stage. The fringes move thank to the electronic box too, such that the PD always measures the same intensity.

If you move the PD in a position, where the loudspeakers are silent, the PM is close to a position, where the probability to detect a photon is almost zero. *Record, store, and analyze the PM signal at this position with both opened interferometer arms and with one arm blocked.* Note that if you block the lower beam too, the stabilization mode fails. Determine the noise contribution of the PM signal by blocking the PM input. *Have you shown Dirac's statement with this experiment? Isn't it possible that two photons can interfere with each other? Please read for this chapter I of [8], the subchapter about photon interference.*

5.3 Transition from particle to wave

Goal: This experiment shows the transition from the quantum mechanical nature of light to the classical nature.

Procedure: Record both the PD and the PM signal with the DSO. Now the PM signal should make the transition to the PD signal. *Operate the DSO in the average mode and store the signal for different number of averages.* Note that you have to wait longer for a stabilized DSO signal as you increase the number of averages. *Store the PD signal and the PM signal (with different number of averages). Read the signals with a suitable software and interpret your results.*

5.4 "Which-path" experiment with a quantum eraser

Goal: With a simple extension of the experimental setup according to fig. 10 you can realize a quantum eraser. By means of two polarizing filters the light gets horizontally polarized in one interferometer arm and vertically polarized in the other. The actual quantum eraser is a polarizer at the output of the interferometer. Its polarization plane can be rotated.

Procedure: Tilt the mirror such that you observe three fringes. The experiment works with another number of fringes too, as long as the PD can distinguish between intensity minimum and maximum. The piezo actuator operates in the mode "manual". Moreover, the PM operates with a bias of seven units (0.7 volts), with block filter, and without the variable filter. The experimental setup is extended according to fig. 10. The laser is orientated such that its polarisation is tilted about 45 degrees with respect to the table plane. *Check with the PD the difference between intensity minimum and maximum for different quantum eraser orientations. For the quantum mechanical description of the quantum eraser, we observe the count rate of the PM depending on the orientation of the quantum eraser by means of the counter (LabView) or the TTL signals recorded with the DSO (analogically to chapter 5.2.1). Why you do not observe any interference if you superpose two orthogonally polarized beams? What is the corresponding quantum mechanical interpretation?*

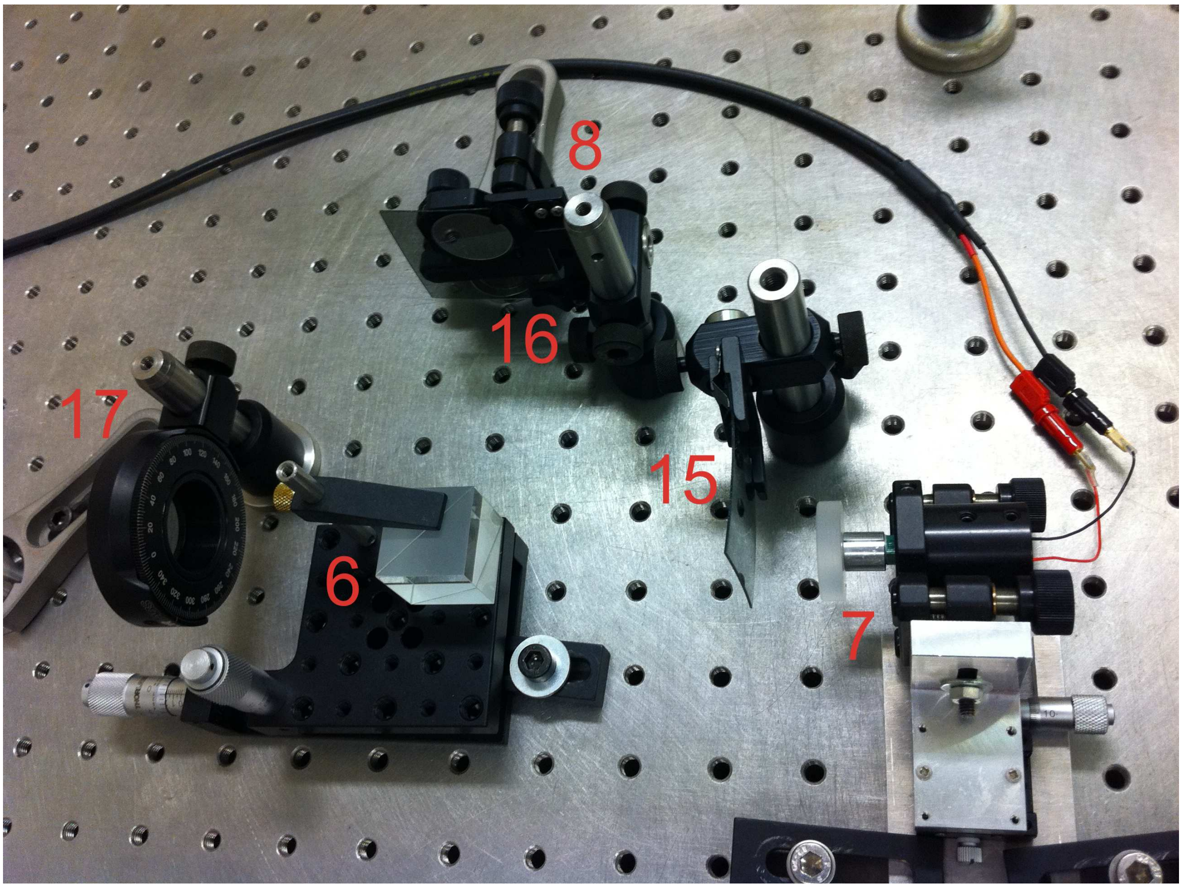

FIGURE 10: Experimental setup of the "Which-path" experiment with the quantum eraser. The elements (6)-(8) build the Michelson interferometer. The setup is extended with three polarizing filters. Filter (15) polarizes the partial beam vertically and the filter (16) the other partial beam horizontally to the table plane. The polarisation plane is marked on the filter with a small cut. At the output of the Michelson interferometer you mount the quantum eraser (17).

References

[1] LOUDON, Rodney: *The Quantum Theory of Light*. Second Edition. New York : Oxford University Press, 1983

[2] GERRY, C. C. ; KNIGHT, P. L.: *Introductory Quantum Optics*. First. Cambridge University Press, 2005

[3] SALEH, Bahaa E. A. ; TEICH, Malvin C.: *Fundamentals of Photonics*. Second Edition. Wiley-Interscience, 2007

[4] VOGEL, W. ; WELSCH, D.G.: *Quantum Optics*. WILEY-VCH Verlag, 2006

[5] KUCERA, P.: Quantum Description of Optical Devices Used in Interferometry. In: *Radioengineering* 16 (2007), Nr. 3

[6] KELLEY, P. L. ; KLEINER, W. H.: Theory of Electromagnetic Field Measurement and Photoelectron Counting. In: *Phys. Rev.* 136 (1964), Oct, Nr. 2A, S. A316–A334. http://dx.doi.org/10.1103/PhysRev.136.A316. – DOI 10.1103/PhysRev.136.A316

[7] DIMITROVA, T. L. ; WEIS, A.: *Mach-Zehnder Interferometer for Demonstrating the Wave-Particle Duality of Light and Quantum Erasing - OPERATING MANUAL.* version 1.02. 2009

[8] DIRAC, P. A. M.: *The Principles of Quantum Mechanics.* Fourth Edition. New York : Oxford University Press Inc., 1958. – 9 S.