A REALISTIC INTERACTION-FREE RESONATOR

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Abstract

A realistic interaction-free resonator which makes use of total reflection and frustrated total reflection is presented. Time evolution and overall losses of the interference in the resonator impose restrictions on the experiment which one can partly overcome by detecting two outputs.

INTRODUCTION

Interaction-free measurements are *void detections* of paths within an interference experiment which therefore destroy their indistinguishability. In 1986 I formulated this in the following way.

"Consider a photon experiment shown in figure 1 which results with an interference in the region D provided we do not know whether it arrived to the region by path s_1 or by path s_2. As is well-known, experimental facts are: If we, after a photon passed the beam splitter B and before it could reach the point C, suddenly introduce a detector in the path s_2 in the point C and do *not* detect *anything*, then it follows that the photon must have taken the path s_1—and, really, one can detect it in the region D but it does *not* produce interference there. Quantum mechanically, if we registered the interference in the region D, we could not find an experimental procedure to directly either prove or disprove that the photon uses both paths simultaneously. However, the fact that by detecting *nothing* in point C we destroy the interference implies that the photon *somehow* knows of the other path when it takes the first one." (Pavičić, 1986; pp. 31, 32)

Photon's "knowledge" about the other path one can employ to detect an object (at point C) without transferring even a single quantum of energy to it. The efficiency of such an application with symmetrical Mach-Zehnder interferometer (shown in figure 1) is ideally only 25% for single detections as shown in Elitzur and Vaidman's (1993) first quantitative formulation of void detections in interference experiments. Therefore several more efficient models have been formulated recently, some of which are reviewed in Paul and Pavičić (1998). A possible application to interaction-free interference erasure is given in Pavičić (1996).

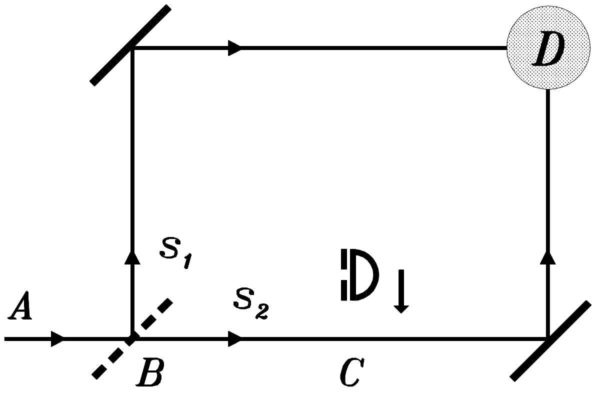

Figure 1. Figure taken from Pavičić (1986). "By detecting *nothing* in the point C we destroy the interference [in the region D]." (Pavičić, 1986; p. 31)

THE EXPERIMENT

Figure 2 shows an outline of the proposed experiment. The resonator used for the experiment consists of Pellin–Broca prisms which are designed so that the entrance and exit faces are at Brewster's angles thus minimizing reflection losses. When there is no object in the resonator, an incoming laser beam is almost totally transmitted into detector D_t and when there is an object, an incoming laser beam is being (ideally) totally reflected into detector D_r. The entrance prism is coupled to the adjacent loop prism by the frustrated total reflection, which is an optical version of quantum mechanical tunneling. Depending on the dimension of the gap between the prisms one can well define reflectivity R within the range from 10^{-5} to 0.99995. The uniqueness of the reflectivity at the gaps and at the same time no reflectivity at the entrance and exit faces of the prisms for each photon is assured by choosing the orientation of the polarization of the incoming laser beam perpendicular to the plane of incidence. As a source of the incoming beam a continuous wave laser (e.g., Nd:YAG) should be used because of its coherence length (up to 300 km) and of its very narrow linewidth (down to 10 kHz in the visible range)

Detailed wave packet calculations carried out by Paul and Pavičić (1997) yield that the efficiency of the suppression of the reflection into D_r is given by

$$\eta = 1 - \frac{I_r}{I_i} = (1 - R_1)(1 - \rho^2 R_2)\,\Phi\,, \tag{1}$$

and the efficiency of the throughput into D_t by:

$$\tau = \frac{I_t}{I_i} = (1 - R_1)(1 - R_2)\,\Phi\,, \tag{2}$$

where

$$\Phi = \frac{\displaystyle\int_0^\infty \frac{\exp[-\mathcal{T}^2(\omega - \omega_{res})^2/2]d\omega}{1 - 2\rho\sqrt{R_1R_2}\cos[(\omega - \omega_{res})\mathcal{T}/a] + \rho^2 R_1 R_2}}{\displaystyle\int_0^\infty \exp[-\mathcal{T}^2(\omega - \omega_{res})^2]d\omega}\,, \tag{3}$$

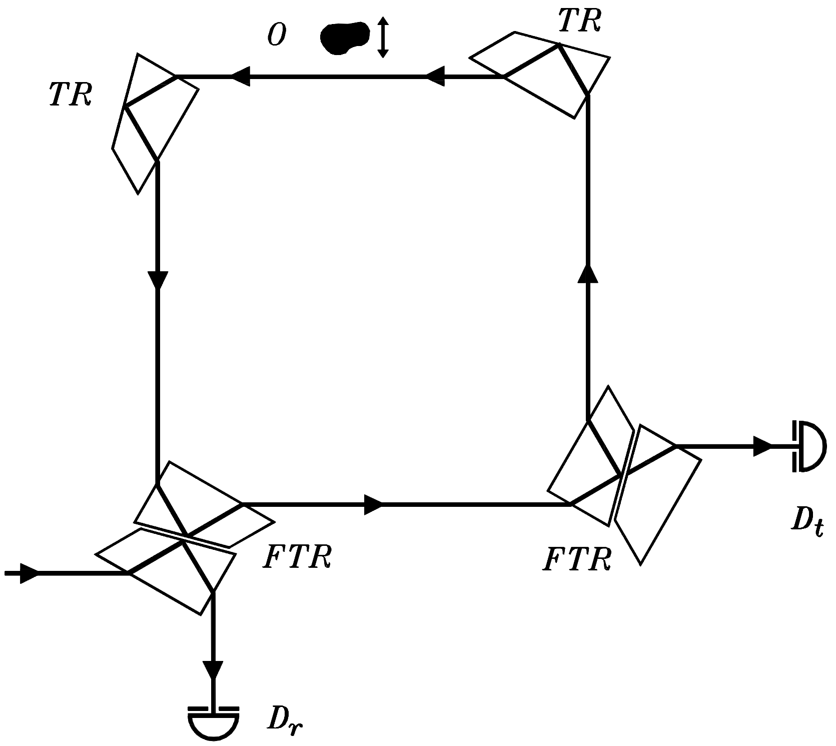

Figure 2. Schematic of the proposed realistic interaction–free device. A single p–polarized photon tunnels (frustrated total reflection) into the resonator made of Pellin–Broca prisms. With a realistic efficiency of over 98% the beam is guided by two total reflections and two frustrated total reflections to exit into D_t when there is no object in the path and is being reflected into D_r when there is.

where $a \equiv \mathcal{T}/T$ is a ratio of the coherence time $\mathcal{T}$ and the round-trip time T; ω_{res} is the selection frequency of the resonator; R is the frustrated reflectivity; $\rho \leq 1$ is a measure of overall losses. For a reliable measurement the coherence length should be long enough to allow sufficiently many round trips. Below we exploit this property to simulate moving of objects in the resonator. Φ turns out to be very susceptible to small changes of ρ so as to yield rather different outputs of τ in opposition to η. Let us have a closer look.

From figure 3 we see that only losses a few percent smaller than the reflectivity at the entrance of the resonator give an acceptable efficiency of the suppression of the reflection into D_r when there is no object in the resonator.

On the other hand the efficiency of the throughput into D_t when there is no object in the resonator is much more susceptible to losses as we can see in the figure 4. This increases the risk of discharging energy stored in the resonator into an inserted object up to 40 % but at the same time enable us to calibrate *grayness* (which can be interpreted as a kind of losses) of objects introduced into the resonator by measuring η. The latter feature reduces the number of required repeating of tests thus balancing the first one.

In figures 5 and 6 we simulate moving of objects inside the resonator by looking at η and τ as functions of low a, the ratio of coherence time and the round-trip time. We can see that even for resonators with the round-trip length long, only objects moving faster than $10^4\,\mathrm{m/s}$ can suffer a discharge. One can also see that the efficiencies stabilize for $a > 100$.

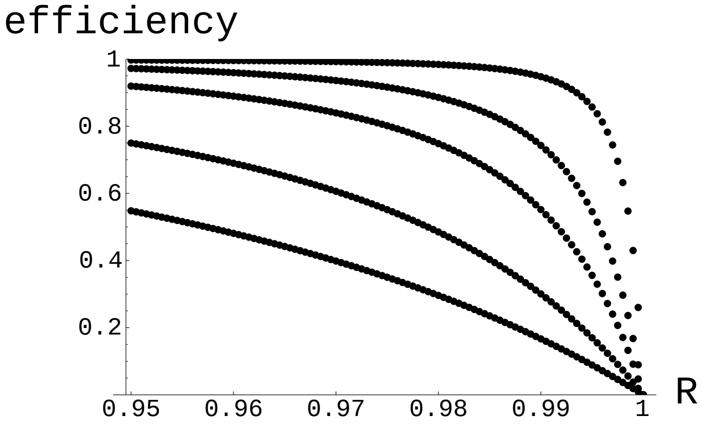

Figure 3. The efficiency of the suppression of the reflection into D_r when there is no object in the resonator, η. R is the frustrated total reflection at the two coupling output prisms. The curves correspond to $\rho = 0.998$ (top), 0.99, 0.98, 0.95, and 0.9 (bottom).

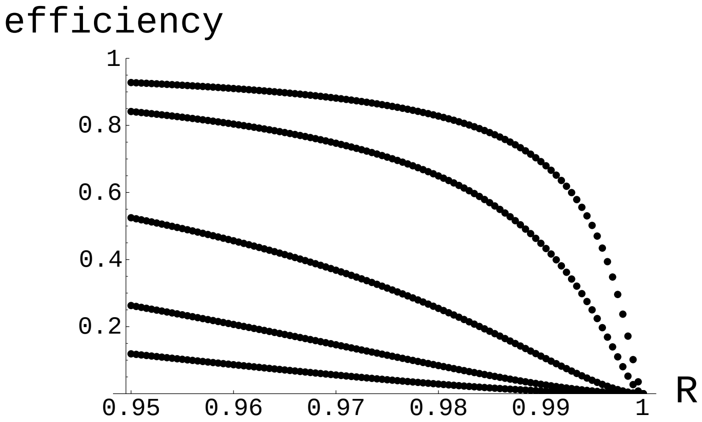

Figure 4. The efficiency of the throughput into D_t when there is no object in the resonator, τ. We again have $\rho = 0.998$ (top), 0.99, 0.98, 0.95, and 0.9 (bottom).

CONCLUSION

We have shown that although with our resonator which makes use of total reflections and frustrated total reflections and Pellin–Broca prisms to minimize reflection losses, thus reducing overall losses to under 2% apparently a realistic interaction-free measurement can hardly be balanced so as to reach an efficiency of over 95%. This nevertheless high efficiency together with a possibility to calibrate grayness of inserted objects by a ratio of reflectivity to transitivity of the resonator makes the device not only very suitable for the foundational experiments but also a good candidate for more general applications. For, although *gray* objects have an increased probability of being hit by a photon, a calibration of the ratio reduces the required repetition of testing objects.

Acknowledgments

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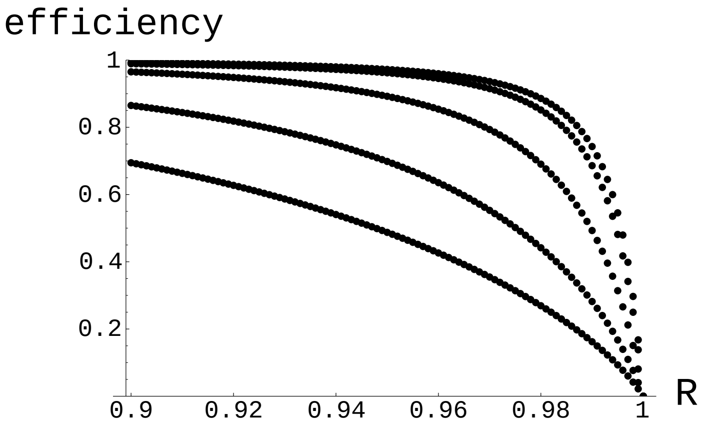

Figure 5. η as a function of a, the ratio of coherence time and the round-tip time for $\rho = 0.99$ and $0.9 \le R \le 1$. $a = 500$ (top), 150, 50, 20, and 10 (bottom).

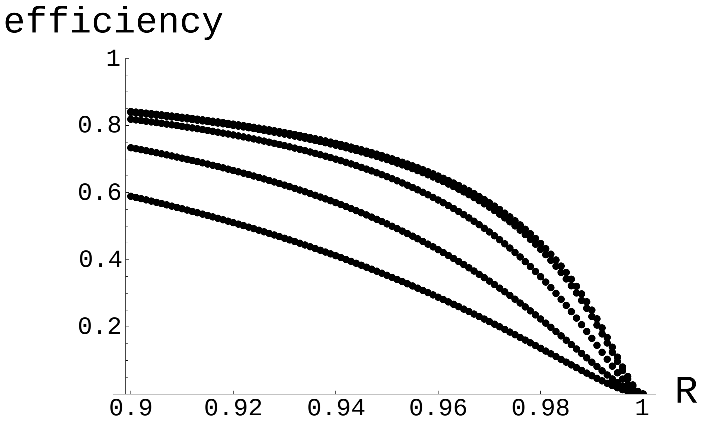

Figure 6. τ as a function of a for $\rho = 0.99$ and $0.9 \le R \le 1.$. $a = 500$ (top), 150, 50, 20, and 10 (bottom).

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