

# Demonstration & implications when 50% beam combiners can behave as 0% or 100% reflector/transmitter inside some interferometers

ChandraSekhar Roychoudhuri<sup>a\*</sup>

<sup>a</sup>Physics Department, University of Connecticut, Storrs, CT, USA 06269

\*Chandra.Roychoudhuri@uconn.edu

## ABSTRACT

The purpose of this paper is to embolden students to raise basic questions regarding the feasibility of “indivisible single photon interference”. We do this by presenting experimental results of well-known classical Mach-Zehnder interferometer (MZI) under two different conditions of beam alignment. We routinely do such experiments in our laboratories. In the first case, we align the light beams on the beam combiner (BC) with their Poynting vectors as perfectly collinear. The 50% dielectric boundary can now transmit 100% of the energy of both the beams into either one of the two MZI output ports, depending upon the relative phase between the two beams combined on the BC from the opposite directions. The dielectric boundary layer actively re-directs the energy from one beam to the other. This is pure classical superposition effect. In the second case, we combine the two beams on the BC with a small intersecting angle. Now the BC functions as a 50% beam splitter to both the beams. One can see spatial fringes as the relative phase varies with spatial distance by placing a photo detector array after the BC. At very low intensity, the quantum properties of the photo detector will become apparent because the photo electrons are discrete and are always bound quantum mechanically to its host molecular assembly; and not because light is definitely quantized. Students can learn to distinguish the pedagogical difference between the Superposition Principle (linear sum of wave amplitudes) and the Superposition Effect (square modulus of the sum of all the wave-induced stimulations) as observable intensity variations due to interaction with materials, classical or quantum.

**Keywords:** Superposition Principle, Superposition Effect, Single Photon Interference, Non-Interaction of Waves, NIW

## 1. INTRODUCTION

### 1.1 Incorporating the role of detectors in the physical detection process

“A photon is what a photodetector detects.” This is apparently a famous saying by the Nobel laureate, Roy Glauber. Then, why do we not write the equation for the Superposition Principle (SP) as the summation of the dipolar amplitude stimulations of the detector molecules induced by two or more incident waves? Therefore, we will utilize this remarkable insight of Glauber to differentiate between the Superposition Principle (SP) and the Superposition Effect (SE). The mathematical expression for SP, as in the Huygens-Fresnel diffraction integral, simply represents the unencumbered propagation of all the Huygens secondary wavelets. The expression for the SP, by itself, is not an observable phenomenon, until some interaction takes place with materials. In contrast, measurable (observable) SE by some detector must be represented by the square modulus of the Huygens-Fresnel integral (or some other waveform), but multiplied by the first order polarizability factor of the molecular complex that one is going to use as a photo detector array. For a classical energy transfer process, as is the case for a dielectric boundary of a beam combiner in an interferometer (to be analyzed in this paper), is a pure classical polarizability. This is built into the derivation of amplitude reflection “ $r$ ” and amplitude transmittance “ $t$ ” for a dielectric boundary layer separated by different refractive indices. Then, SE is a completely classical phenomenon, known since Newton’s time. Newton was the inventor of the Newton Interferometer [1]. When the detector is a modern quantum mechanical device, where quantum mechanically bound electrons are released by the incident light, SE manifests as quantum mechanical phenomena. The detector stimulation is guided by the first order quantum mechanical dipolar polarizability of the detector molecular complex. For this second case, the superposition effect is conveniently formulated by semi-classical mathematical model. Several well-known authors [2-6] have promoted this semi-classical model. In classical interferometry and scattering, SE represents energy re-direction. When one uses quantum detectors, a “quantum cupful” of energy is absorbed for the

release of each discrete photoelectron bound to its molecular complex. Thus, the quantumness resides in the detector, not in the electromagnetic waves.

Each Poynting vector, belonging to each one of the wave group, guides the diffractive evolution, as per Huygens-Fresnel diffraction integral. Wave groups can co-propagate and cross-propagate through any linear medium, while remaining unperturbed by each other's presence. This is Non-Interaction of waves (NIW) [5]; this is built into most of our mathematical formalism of optical phenomena, although not mentioned explicitly as such. Without interaction with materials, classical dielectric boundary layer or photoelectric material, the superposition effect does not become manifest.

## 2. MACH-ZEHNDER INTERFEROMETER (MZI) IN SCANNING MODE: FULLY CLASSICAL SUPERPOSITION EFFECT

### 2.1 The MZI experiment

Since the invention of coherent laser beams, people have been carrying out Mach-Zehnder Interferometry (MZI) with collinearly superposed collimated beams on the beam combiner (see Fig.2.1). One can detect interference fringes as intensity variations only when there is a relative phase variation between the two superposed beams. When the two Poynting vectors of each of the two pairs of output collimated beams are perfectly collinear, there is no relative phase variations across the parallel wave fronts. The intensity remains uniform. To observe fringes (intensity variations), one has to introduce a relative phase delay by scanning one of the mirrors. In our case, it is the mirror M1 (Fig.2.1). Let us assume that the two incident beams on the BC from M1 and M2 are exactly equal,  $a_1 = a_2 = a$  (see Eq.2.1). Under this condition, scanning the mirror M1 introduces varying  $\tau$ . This will make the two detected signals by D1 and D2 to oscillate as  $(1 - \cos 2\pi\nu\tau)$  with out of phase in their intensity curves (Fig.2.1.2), between zero (0%) and one (100%). Eq.2.1 calculates the resultant superposed energy received by the detector D1, where one of the two beams, the externally reflected beam, experiences a  $\pi$  phase shift. This is accommodated in the equation as the  $\exp[i\pi]$ :

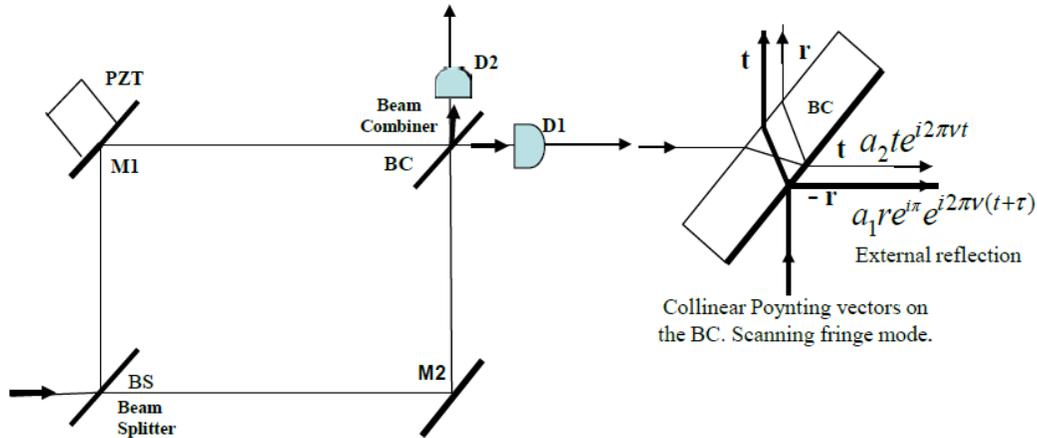


Figure 2.1.1. **Left diagram:** A Mach-Zehnder interferometer in scanning mode with the Poynting vectors of both the output beams in the two ports out of the beam combiner BC, are perfectly superposed and exactly collinear. Under this condition, to measure the fringes, one has to introduce a relative phase delay between the two beams by scanning one of the mirrors, here M1. **Right diagram:** Enlarged view of the ray-diagram for the two pairs of output beams out of the BC. We have also designated the output amplitude coefficients for all the output beams. Note the  $\pi$  phase shift experienced by the “externally reflected” beam.

Notice that the “passive” beam combiner BC executes the operation of how much energy to direct in which port. The output energy oscillates between 0% and 100%. This depends upon the phase conditions of the two incident beams on the dielectric boundary from the two opposite directions. The  $\pi$  phase shift for external reflection becomes an important physical condition for the phenomenon we are studying.

$$\begin{aligned}
 D(\tau) &= \left| a_1 r e^{i\pi} e^{i2\pi\nu(t+\tau)} + a_2 t e^{i2\pi\nu t} \right|^2 \\
 &= (a_1^2 r^2 + a_2^2 t^2) - 2a_1 a_2 t r \cos 2\pi\nu\tau \\
 &= 2a^2 [1 - \cos 2\pi\nu\tau]; \text{ when } r^2 = t^2 = 0.5 \text{ and } a_1 = a_2 = a
 \end{aligned}
 \tag{2.1}$$

In the beginning, relative path-difference between the two arms of the MZI is set to zero. This is a normal practice. The path delay, for the beam coming from the stationary mirror M2 and after being reflected by the BC, remains fixed. However, it does suffer from a fixed extra  $\pi$  phase shift due to the physics of “external reflection” [7]. The path delay for the beam coming from scanning mirror M1 experiences a sinusoidal oscillation when the scanning voltage is applied to M1. This beam does not suffer from any phase shift due to the physics of transmission through the BC.

Consider now the port for the detector D1. Whenever the beam sent by the scanning mirror M1 will have a relative phase shifts of  $\pi, 3\pi, 5\pi$ , etc., (zero or modulo- $2\pi$  relative phase delay); the stimulation of the dielectric boundary to the outer side of the BC will experience preferred in-phase stimulations and will send the propagating wave energies of both the beams to this right-going port. For the up-going port, the inner dielectric boundary will experience zero stimulations due to out-of-phase condition on the inner boundary of the dielectric layer. The energy transmittance will be zero in this up-going port. Similarly, when the beam from the scanning mirror M1 experiences relative phase delay of  $0, 2\pi, 4\pi$ , etc., the two up-going beams are stimulating the inner-side of the dielectric boundary with their Poynting vectors in-phase in the up-going direction. The transmitted beam coming from M2 is transmitted without the  $\pi$  boundary phase delay. Then all the energy goes in the up-going beam. The right-going beam becomes extinct.

Functionally, a normally passive 50% beam splitter has become “active” under the influence of excitations from opposite sides with two beams, one of which delivers oscillatory phase. Under this condition, its effective reflectance oscillates from 0% to 100%. In other words, depending upon the phases of the superposed beams, a 50% beams splitter can become energy re-director.

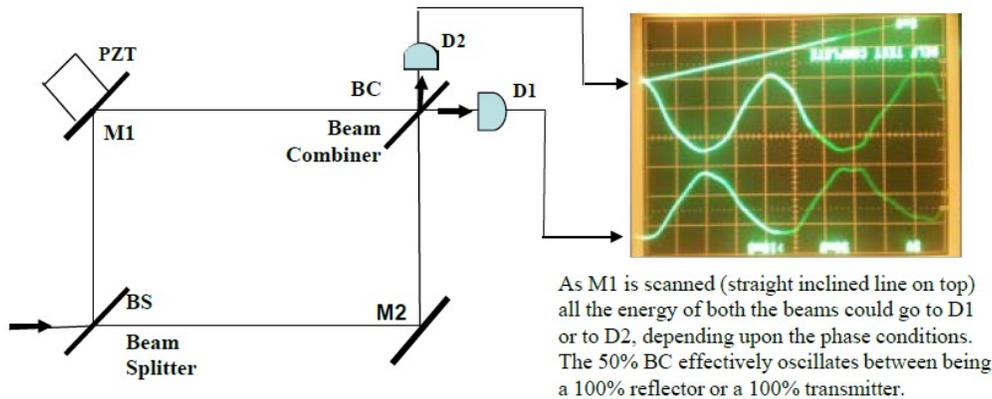


Figure 2.1.2. **Left diagram:** the same scanning MZI as in Fig.2.1. **Right diagram:** An oscilloscope snap shot of the scanned intensity variation in the two output ports of the interferometer. It is clear that one the intensity registered by D2 is minimum, that due to D1 is maximum.

This is fully classical superposition effect. We do not need to treat either the EM waves, or the macro dielectric boundary molecular assembly by using quantum mechanics. Similar situation arises in scattering phenomenon with fine particles or ground glass surface. If one stimulates a small scattering center with two beams having exactly equal amplitude but with opposite phase; it will fail to scatter energy in the forward direction [8].

Fresnel calculated the reflection and transmission coefficients for light waves from a dielectric boundary, using the simple physics of boundary conditions during early nineteenth century, well before Maxwell formulated his wave equation. One can find the derivations in most basic optics texts [6]. One can derive the  $\pi$  phase shift with simpler math using the principle of conservation of energy [see section 3.3 in ref. 5].

## 2.2 Implications: Can “indivisible single photon”, if existed, could generate superposition effect?

In the video experiment depicted in Fig.2.2.1, we deliberately, but separately, blocked the beams coming out of M1 or M2, one at a time, to observe the need for the simultaneous presence of the two signals on the beam combiner (BC) from the opposite sides. When the MZI beams remain un-blocked, the two beams from the two output ports, projected on a screen, keeps oscillating between bright and dark. However, when either one of the two beams is blocked, the BC becomes a stable 50% beam splitter. The screen shows two equally bright and steady spots (not shown in the Fig.2.2.1).



**Figure 2.2.1.** [Video online] Mechanically blocking any one of the two incident beams on the beam combiner from the opposite sides converts the beam combiner into a regular 50/50 beam splitter. Blocking destroys the emergence of the superposition effect; which is its capability to re-direct 100% of the energy out of the two beams into one of the selected direction, depending upon the phase condition, as the mirror M1 keeps scanning (see Fig.2.1.2).

Now, let us discuss the question raised in the section heading. Can a single photon interfere all by itself? Our classical superposition experiments clearly demonstrates that the two opposing beams must be simultaneously present on the beam combiner (BC) from the opposite sides to generate the superposition effect. Obviously, a single “indivisible photon” can stimulate the BC only from one side or the other. We have demonstrated that under such condition the BC behaves as a regular beam splitter without the capability of generating any superposition effect. There is nothing quantum mechanical at all in this experiment. Accordingly, one is forced to conclude that EM waves are Maxwellian classical waves. Would reduction of the intensity of the incident beam to extremely low level change the observed outcome? If it does, one has to postulate that the properties of EM waves dramatically change at very low intensity!

The experiment in the next section uses *non-collinear beams* in the same MZI, which makes the BC behave as a regular beam splitter even when both the beams are present at an angle. Intensity variation can be registered as spatial fringes, but external to the MZI with some detector array. Since most detector arrays are quantum mechanical, one would notice discreteness in the registered signal. However, this is not due to light being “indivisible quanta” in its propagation; but because the photoelectrons in all materials are bound quantum mechanically with characteristic dipolar resonance frequency  $\nu$  requiring absorption of specific “quantum cupful” of energy  $h\nu$  [6].

## 3. MACH-ZEHNDER INTERFEROMETER (MZI) IN FRINGE MODE: SEMI-QUANTUM MECHANICAL SUPERPOSITION EFFECT

Traditionally, we have been using interferometers in fringe mode where the Poynting vectors of the two superposed beams are at an angle, as in Fig.3.1. The two beams, propagating at an angle out of the beam combiner, are superposed on the plane of the detector as  $E(t, \tau)$ . This can be represented by the summation of the two plane wave amplitudes with linear relative temporal delay  $\tau$ , where the reflected wave is  $a_1 r e^{i\pi} \exp[i2\pi\nu(t + \tau)]$  and the transmitted wave is  $a_2 t \exp[i2\pi\nu t]$ . In the absence of any detector, the two beams will cross propagate through each other completely unperturbed by each other as if they have never experienced each other; even though we present them as a summation:

$$E(t, \tau) = a_1 r e^{i\pi} e^{i2\pi\nu(t+\tau)} + a_2 t e^{i2\pi\nu t} \quad (3.1)$$

When one inserts a detector array in the desired plane, the molecular complexes will experience simultaneous dipolar amplitude stimulations induced by both the fields. We represent this stimulation (*light-detector interaction*)

by  $\chi(\nu)E(t, \tau)$ , where  $\chi(\nu)$  represents the linear dipolar polarizability of the detector materials, sensitive to the allowed quantum mechanical vibration frequency  $\nu$  for the bound electrons in the detector. The detector responsivities are frequency sensitive.

$$\chi(\nu)E(t, \tau) = \chi(\nu)a_1 r e^{i\pi} e^{i2\pi\nu(t+\tau)} + \chi(\nu)a_2 t e^{i2\pi\nu t} \quad (3.2)$$

The Superposition Effect (SE) become manifest as some changes in the detected energy distribution. The recipe to find the energy absorption is always the square modulus of the expression for the complex amplitude stimulation.

$$\begin{aligned} D(\tau) &= \left| \chi(\nu)a_1 r e^{i\pi} e^{i2\pi\nu(t+\tau)} + \chi(\nu)a_2 t e^{i2\pi\nu t} \right|^2 \\ &= \chi^2 \left| a_1 r e^{i\pi} e^{i2\pi\nu(t+\tau)} + a_2 t e^{i2\pi\nu t} \right|^2 \\ &= \chi^2 [(a_1^2 r^2 + a_2^2 t^2) - 2a_1 a_2 t r \cos 2\pi\nu\tau] \end{aligned} \quad (3.3)$$

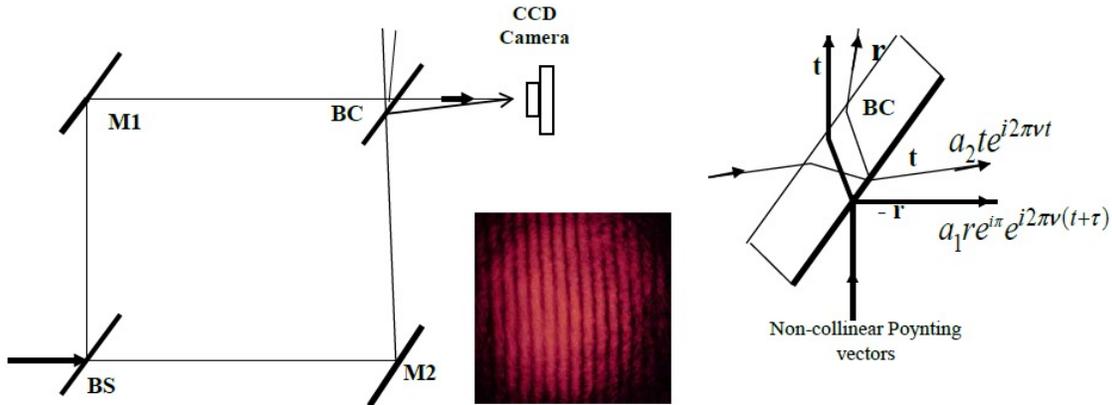


Figure 3.1. **Left diagram:** A typical Mach-Zehnder interferometer in fringe-mode where the two beams are combined on a beam combiner (BC) at an angle such that the respective beam Poynting vectors are at an angle. Under this condition, fringes can be made visible by a detector array (middle diagram). **Right diagram:** Enlarged ray diagram on the BC underscoring that there is a  $\pi$  phase shift for “external reflection”, well known from classical electromagnetism. This  $\pi$  phase shift is of critical importance in tracking the exact fringe location when they are to be numbered properly for precision interferometry [1]. See fig.1.3 in ref.5.

Here, the detector array, with its intrinsic quantum properties, is carrying out this physical process. We have maintained the expression for the EM waves as classical field. Each molecular complex, holding an excited but bound photoelectron, behaves as a *quantum-cup* that requires  $\Delta E = h\nu$  before it can release the electron [6,8,9]. Therefore, in this case, the energy transfer process is quasi quantum mechanical [2-5]. This is in contrast to the last section where the SE was a completely classical energy transfer process. Clearly, *the photon concept arises only when the detector is quantum mechanical, displaying the quantum-cup property*. Of course, spontaneous emissions by atoms are also quantized to release  $\Delta E = h\nu$  quantity of energy and that can be explained as atoms releasing a quantum cupful of energy, which then evolve as classical wave packets.

When the incident radiation is a very narrow band source like a single mode laser,  $\chi(\nu)$  can be assumed a constant  $\chi$  and can now be taken out of the square modulus operation without violating any mathematical rule. The second line of Eq.3.3 represents this new mathematical expression. Unfortunately, then this second line *tacitly implies* that the set of cross propagating wave amplitudes, by themselves, are generating the re-distribution of field energy and hence the fringes. This would be an erroneous assumption out of a mathematically “correct” expression

$$D(\tau) = 2\chi^2 a^2 [1 - \cos 2\pi\nu\tau]; \text{ when } r^2 = t^2 = 0.5 \text{ and } a_1 = a_2 = a \quad (3.4)$$

Eq.3.3 can be further simplified to Eq.3.4 under the condition the final beam combiner has a perfect 50% reflecting coating,  $r^2 = t^2 = 0.5$  and  $a_1 = a_2 = a$ . It is quite customary in many single-photon counting experiments to use this “potentially” possible condition. Then, they count the individual “clicks” of current pulses, containing millions or billions of electrons in each pulse, generated by the photoelectron generator followed by electronic amplifiers and

electronic counters. Such experiments, when done with great care, definitely assures us that electrons are quantum mechanical entities, and bound in materials quantum mechanically. However, this does not assure us that the EM waves are definitely quantized. It could be; but the postulate of “indivisible light quanta” is not a definitive conclusion out of such experiments. Note further that Eq.3.4 demands  $a_1 = a_2 = a$ . It becomes a further stretch of logic when we try to use this condition, along with the slow rate of count of “clicks”, to claim that we only had a single photon in the interferometer that generated the superposition effect. We know from the experiment described in the section 2 that we must have physical signals from the both sides of the BC to generate any superposition effect. Can we claim that, when the beams are directly superposed on the detector at an angle, only one of the beams is needed to generate the superposition effect? Let us also note that the energy for a single visible “photon” would be about  $h\nu \sim 6.63 \cdot 10^{-34} J \cdot s \times 10^{14} / s = 6.63 \times 10^{-20} J$ . We still do not have any meters to measure energy precisely to this accuracy. Our *quantum cup* postulate implies that at such low intensity level, the detectors will not be able to fill up their individual cups to release photoelectrons. An alternate “photon clump model has also been proposed [10].

Let us scrutinize the Eq.3.3 again. The intensity term,  $\chi^2 [(a_1^2 r^2 + a_2^2 t^2) - 2a_1 a_2 tr \cos 2\pi\nu\tau]$ , depends upon both the amplitude factors. In reality, even our mathematics that we take great pride in, clearly tells us that quantum detectors are *quantum cups*, which can be filled up with contributions from all the participating wave packets proportional to the quadratic powers of all the amplitudes. Eq.3.3 does not support the postulate that superposition effect can be generated by a single “photon” from one or the other beam. Besides, we have amply demonstrated [6,8,9] that light beams do not interfere by themselves (the NIW property). The word “superposition” and our mathematical equations representing “superposition” clearly indicate the necessity of simultaneous presence of multiple signals to interact with some material medium to generate superposition effect.

#### 4. ACKNOWLEDGEMENTS

The author would like to acknowledge that A. Michael Barootkoob has carried out the experiments presented in this paper under the supervision of the author.

#### REFERENCES

- [1] D. Malacara, Ed., see Ch.1 in [Optical Shop Testing], 3<sup>rd</sup> ed. (2007).
- [2] E.T. Jaynes and F. W. Cummings, “Comparison of Quantum and Semi-Classical Theories of Radiation with Application to the Beam Masers.”, Proc. IEEE Vol. 51, 89 (1963).
- [3] W. E. Lamb, Jr., [Interpretation of Quantum Mechanics], Rinton Press, Inc., (2001).
- [4] G. Grynberg, A. Aspect and C. Fabre, [Introduction to Quantum Optics: From the Semi-Classical Approach to Quantized Light], Cambridge U. Press, (2010).
- [5] Cray, M.; Shih, M.-L. & Milonni, P. W, “Stimulated emission, absorption, and interference”, Am. J. Phys., Vol. 50 (11), pp.1016-2021 (1982).
- [6] C. Roychoudhuri, [Causal Physics: Photon Model by Non-Interaction of Waves]; Taylor & Francis, Hardbound, 2014; Paperbound (2017).
- [7] E. Hecht [Optics], 5<sup>th</sup> Ed., Addison Wesley (2016).
- [8] C. Roychoudhuri, “Consequences of repeated discovery and benign neglect of Non-Interaction of Waves (NIW)”, Proc. SPIE ETP100-36 (2017).
- [9] C. Roychoudhuri, “Re-energizing Enquiry among our young professionals”, Proc. SPIE ETP100-43 (2017).
- [10] E. Panarella, “‘Single photons’ have not been detected. The alternative ‘photon clump’ model”, Proc. SPIE Vol.5866, paper #39 (2005).