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What are the processes behind energy re-direction and re-distribution in interference and diffraction?

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Abstract

The interpretation of the detection of very slow rate of photo counts in interference and diffraction experiments have given rise to the prevailing interpretation that photons interfere by themselves and they are indivisible, albeit non-local. The purpose of this paper is to inspire the development of alternate models for the photons by underscoring that, in reality, light does not interfere with light. The effects of superposition, registered as interference fringes, can become manifest only when a suitable detector can respond simultaneously to all the superposed light beams separately arriving from all the paths (or, slits). It should be a strictly causal process. In fact, different detectors with different quantum properties, report different results while exposed to the same superposed fields. Interference and diffraction effects are always observed as fringes through the processes of re-distribution and/or re-direction of the measured energy of the superimposed fields. Accordingly, we present a number of experiments, actual and conceptual, which highlight the contradictions built into the notion of non-locality in interference. A closer examination of these experiments can guide us to develop a conceptually congruent and causal model for both the evolution of photons and the interference (diffraction) effects by adapting to the classical diffraction theory. This theory has been correctly predicting the characteristics of light whether it is star light propagating through the inter galactic space, or nano tip generated light propagating through complex nano photonic waveguides.

Key words: non-interference of light beams; locality and causality of interference; single photon interference; semi classical approach to interference.

1. Introduction

Background. The predominant view [1, 2] of the nature of light is that it constitutes indivisible packets of electromagnetic energy $\Delta E = h\nu$, where ν is the Fourier monochromatic mode of oscillation of the vacuum field (cosmic medium that sustains everything). But this paradigm is forced to accept self contradictory interpretation that a photon is simultaneously indivisible and non-local (represented the by infinite extent Fourier monochromatic oscillation). This, of course, has nurtured a wide variety of non-causal interpretations for the "quantum world", not observed in the "classical world", like "delayed choice", "many worlds", "teleportation", etc. [1, 2]. The indivisibility interpretation comes from the combined "necessary and sufficient" assumption that discrete "clicks" registered by our quantum mechanical detectors constitutes the ultimate proof of indivisible photons. Even though semi classical treatments have successfully demonstrated the analytical explanation of photoelectric effects based on classical electromagnetic fields and quantum detectors [3, 4, 5], including very low counts influenced by background fluctuations [6-8], the dominant opinion remains in favor of indivisible but non-local photon because of disagreements on how to interpret micro cavity QED effects [9, 10] and coincidence counting originating from entangled "photon" producing sources [11].

Reality Ontology. The epistemological assumption behind this paper is that we cannot have an unbridgeable "causal classical world" built out of the "non-causal quantum world". The macro universe, from inanimate sand particles, and animate single cells on the Earth to the stars and galaxies in space, all are evolving with a high degree of causality and yet they are sustained through incessant interactions between the molecules, atoms, elementary particles and "photons" of the micro universe. Our position is that we should be able to find some conceptual continuity (congruency) between the micro and the macro universes as they are one and the same. We have been interpreting experimental observations, especially, the interference and diffraction fringes, without explicit attention to comprehending the actual, physical, processes behind our recording the discrete "clicks" and their accumulation as observable fringes. The thesis of this paper is that a critical exploration of the processes behind the fringe formation as *local* re-distribution and/or re-direction of the collective field energy (in interference and diffraction experiments) as a result of the detector response, could lead us to find the conceptual congruency between the classical and the quantum worlds.

Detector hypothesis. Our detectors that register the observable fringes are "classical" in size but quantum mechanical in action as they constitute many quantum mechanical devices (array of atoms or assembly of atoms). Each of these component QM detectors is highly localized within the macro detector and also within their own quantum mechanically defined average physical, nanometric size, while carrying out quantum mechanical undulations and other agitations due to ever present thermal and other variety of background fluctuations like zero point energy, dark energy, dark matter, etc. (that we do not yet fully comprehend). The spatially modulated field energies, constituting the superposition of actual multiple fields, must simultaneously stimulate these highly local and microscopic detector elements for them to undergo observable transformations. Then we can raise the following two questions. First, (i) does the original incident field have the mysterious capacity to sense the distribution and orientation of all the parts of an interferometric or a diffractive apparatus and accordingly re-direct and/or re-distribute its energy spatially on the detector array? All natural entities, undulating fields or particles alike, must contain finite amount of energy and accordingly must have a finite space and time duration and finite velocity. It is the assumption that the indivisible and independent photons arrive only at the bright fringes, sensing the entire apparatus non-locally, gives rise to the non-causal possibilities like "delayed choice", "teleportation", etc. Second, (ii) does the original field divides itself, as per classical wave model, into multiple field entities and after causal propagation and superposition, and collectively re-distribute their field energy to be recorded as orderly fringes by the detector? While this apparently causal model is centuries old, it has not succeeded in resolving the non-causal interpretations simply because we have been ignoring the blatant fact that light beams do not interfere with each other in the absence of materials (dipoles); actually they propagate through each other without influencing each other. So, we propose that the exploration and understanding the actual physical processes behind detection could restore the causality. *In the causal and real world, the principle of superposition can become manifest to us only through the material dipoles while they experience and respond to the simultaneous presence of multiple field entities on them.* This is why the debate on in-determinability of 'which way through the interferometer the photon has traveled' has remained as a blind alley.

What is a Photon? Is it possible to find a single self consistent description of the processes behind fringe formation (i) whether the superposed fields contain energy equivalent to one or very many units of $\Delta E = h\nu$, and (ii) whether the units behave collectively or as independent and indivisible entities? We do assume that space and time finite atoms and molecules emit discrete packets of EM energy, the photons, as has been correctly formulated by QM. However, we are going to follow the success pattern of Huygens-Fresnel (HF) principle (with its mathematically self consistent modern improvements [12]). We are assuming that all photons start with their own quantum of energy $\Delta E = h\nu$ as a space and time finite wave packet, which is a mode of oscillation of the vacuum with the unique carrier frequency ν. The wave packets evolve and propagate following the H-F diffraction integral, allowing association with other wave packets of the same carrier frequency. Atoms and elementary particles with non-zero rest mass are localized entities and accordingly require a different model for interference and diffraction, which will be dealt with elsewhere.

The range of success of HF integral in conjunction with Maxwell's wave equation is staggering. It accurately predicts the transformation of diffraction patterns from very complex and rapidly changing near filed patterns to angularly stable and sustainable far filed pattern in free space when simple or most complex apertures rupture spatially coherent wave fronts. However, the evolution of diffraction patterns (fringes) are more complex and enigmatic compared to interference fringes due to superposed beams of negligible diffraction. Spatial near filed patterns are rather complex and evolve rapidly, as if the various ruptured wave fronts produced by a grating from a single coherent wave front propagate without modifying (or, operating) on each other. But, toward the far field, the evolution of the pattern becomes slow and eventually it assumes an angularly stable and sustainable pattern as if the diffracted wave fronts have collectively remolded themselves into an angularly stable and sustainable new wave packet (or, multiple wave packets as in grating orders) to minimize the energy loss as it propagates further.

HF principle correctly predicts the emergence of spatial coherence out of incoherent complex sources like discharge tubes in labs. or distant stars (van Cittert-Zernike theorem)[12]. It correctly derives the spatial eigen mode structures of most complex laser cavities where the wave front emerges through the collective diffraction of randomly emitted spontaneous photons (wave packets) that gets selectively amplified through stimulated emissions [13]. It is now correctly predicting the propagation modes of near and far field patterns due to nano photonic waveguides or nano photonics tips [14]. The study of diffraction phenomenon indicates that EM wave is a collective and cooperative phenomenon in the vacuum as the classical wave equation implies. Whether emitted spontaneously or stimulated from many individual atoms or disrupted by diffracting apertures, the multitudes of wave packets collectively and cooperatively evolve into an angularly sustainable but well defined wave form. Understanding this complex process of evolution of new filed pattern from a ruptured coherent field may lead us to better understand the evolution of complex photon wave fronts starting from multitudes of statistically random photons. We believe that the diverse and complex variations in "photon counting statistics" reported in the literature [1], can be derived by semi classical theory if one allows the statistically finite number of wave-packet photons to diffract from the source through mutual superposition and derives the effective field on the detector at a finite distance from the source. In fact, we predict that since the very near field and the far field diffraction patterns are dramatically different, the corresponding temporal "photon counting" statistics will also vary for a typical "thermal" source due to collective evolution (propagation) of photons. However, the situations in micro cavity QED experiments are very different where the photons do not have the space and time to evolve as free space EM waves [9, 10]. It may be very instructive to find out all the situations where this model of classical wave packet for the photons clearly breaks down.

Contents. We present a series of actual and contrived experiments, both in interference and in diffraction, to underscore that the interference and diffraction fringes require signals to divide and travel through all the available paths and be present on the detector simultaneously. The detectors require actual superposition of multiple waves carrying multiple phase information on them to be able to report any "superposition effect". In fact, the observed effects of superposition for the same set of fields differ with different detectors [15] based on their differing quantum response properties, like energy gaps and energy levels and their widths.

2. Local energy re-distribution belonging to different laser modes at high resolution by multiple beam superposition

This is a conceptually simple experiment that we have carried out [16] to demonstrate that it takes real physical superposition of a number beams with a periodic delay by replicating the original beam to be analyzed for its frequency content. In general, the energy separation (re-distribution) becomes apparent only when detected. This is to underscore the point that the principle of superposition becomes manifest through the active participation of a detector. Fig.1 shows the schematic diagram of the experiment. A two-mode (two frequencies) He-Ne laser beam was directed at an angle toward a high resolution Fabry-Perot interferometer (FP) with plane parallel mirrors. The beam was replicated into a set of spatially displaced beams, as if they were coming out of a grating. The beams were then physically superposed by a focusing lens on a tilted glass plate. When the transmitted beam was used to sharply re-image and enlarge the focal plane by a microscope objective, one could see the repeated fringes due to the two laser frequencies when

the FP was set properly [16]. However, the reflected portion of the focused beam diverged out as spatially separated and independent beams, mirroring their origin. When we separately analyzed any one of these fanned out beams by another FP, they showed to contain both the laser mode frequencies. Conceptually there are no surprises if one things along the line of classical geometrical or physical optics. However, if the energy re-distribution were determined non-locally by the entire apparatus based on the paradigm of arrival and non-arrival of indivisible photons, then the re-emergence of all the focused beams as unperturbed, independent beams would not have been possible. In this experimental arrangement, only detectors can experience the apparent energy separation corresponding to the two different frequencies; the focused light beams did not redistribute their energy in the focal plane. The photons directed to travel through an FP at an angle experience it only as a pair of beam splitters, but not as a frequency sensitive resonator. Note also that if the incident light beam is a pulse shorter than the round trip delay between the mirrors, the train of pulses will never exist simultaneously at the focal plane and correspondingly there will be no interference (spectral) fringes [17], even though the single incident wave packet will be split into N-delayed packets, will travel through the N-distinct paths and cross the focal plane.

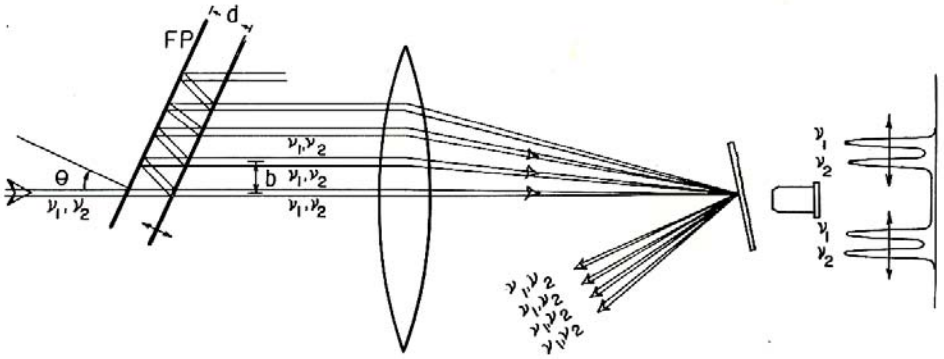

Figure 1. Experimental demonstration of non-interference of light beams in spite of crossing each other at the focal plane, while at the same time, delivering the classical spectrometric information when a detector is placed in the plane of superposition [16].

3. Locking independent laser array by near field Talbot diffraction

More than 100 years ago Talbot discovered that an amplitude grating reproduces itself as a perfect image at a distance ($2D^2/\lambda$), where D is the grating periodicity [18]. We have exploited this near field diffraction phenomenon to phase lock (enforced collaborative, laser oscillation) on a periodic array of independent diode lasers [19]. The relevance of this experiment in the context of this paper is again the causality and locality of the interference and diffraction phenomena. Fig.2 presents the summary of the effects and some results of mode control. A flat mirror at the half-Talbot distance can enforce spatial mode locking because the feedback into the independent laser element becomes maximum when their individual image falls back on themselves. This becomes possible only when their statistically random spontaneous emissions starts accidentally to match up in their phase and their local superposed effects strengthen the stimulated emission. Here, the excited laser molecules act as the material detectors to make the superposition effects become manifest. If the mirror is displaced from the (D^2/λ) position, the "superposed" diffraction pattern does not match the phase condition on the laser array and they do not get phase locked. Further, if the Talbot mirror is removed, the "diffraction" pattern evolve as incoherent superposition of the N individual laser beams. The Talbot images in the near field are actually quite complex along with phase shifts and there are actually multiple Talbot planes, shown in Fig.2 (top) [18]. We have exploited the second sub-image plane to discriminate against higher order spatial modes by inserting appropriate phase aperture. The model of photon as an indivisible but non-local vacuum oscillation (Fourier monochromatic mode) brings conceptual confusion as to how it can undergo such rapid spatial variations across such a large angular and spatial domain in the near field without invoking classical diffraction theory. Lande's quantized scattering model [20] will require arbitrary changes in the quantization of the angles to different sets of values depending upon where one places the detector plane (various Talbot images or the far filed). This will imply pre-cognition capability by the photons as to where the experimenter places the detector. In contrast, the model of photon as a classical, time-finite wave packet with a unique carrier frequency, propagating out as per

classical diffraction and superposition theory while freely associating with other wave packets, gives us all the complex results along with a causally congruent "picture".

4. A simple two beam holography experiment

We know that when two light beams cross each other, they propagate out unperturbed by each other. Light does not interfere with light. But, when we place a holographic plate to record the fringes, we perturb the two wave fronts due to spatially differential absorption of energy during the time of exposure [21]. So, the two beams should suffer amplitude modulations, giving rise to some diffraction effects. To our "first order" accuracy we could not detect any diffraction during the live detection process of the fringes with a hologram at the beam intersection (Fig.3 'Bottom-right'). We repeated the experiments from $1/30^{th}$ of a second to 180 seconds of exposure by reducing the beam intensity by

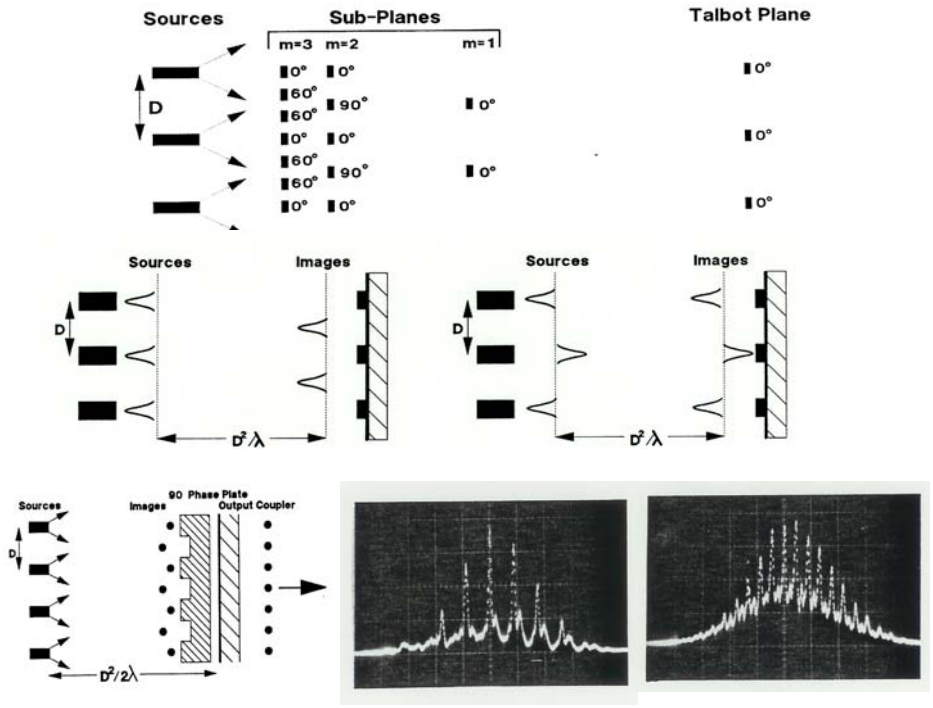

Figure 2. Exploitation of the complex periodicity in the near filed diffraction to phase lock an array of independent lasers. **Top:** Various Talbot images due to diffraction of a coherently illuminated grating or a coherent laser array. **Middle-left:** Laser array oscillating in the fundamental mode and the corresponding Talbot image. **Middle-right:** Laser array oscillating in the highest order spatial mode and the corresponding Talbot image. **Bottom-left:** A phase filter in the sub-Talbot cavity to impose oscillation in the fundamental mode. **Bottom-middle:** The far filed of a 30-element diode array oscillating in the fundamental mode with spatial filter. **Bottom-right:** Far field for the same array oscillating in the higher order mode without the spatial filter [19].

a factor of 5.4×10^3 to keep the hologram density (after similar development conditions) same for reconstruction purpose. Unlike photo refractive and photo chromic materials, photographic plates do not experience any appreciable index change with low light exposure in the absence of development. From this stand point, the absence of diffraction by any of the crossing beam during live exposure may be acceptable. However, we are asking a more subtle question. How do the light beams propagate unperturbed even during the process when the beams are depositing spatially varying energy? *Is it because the finite time that it takes for the detecting dipoles to absorb energy provides the light beams the time to readjusts their original wave front integrity?* We know that the beams suffer diffraction when the developed hologram is placed back in the original position as it imposes stationary

amplitude or phase perturbations on the beams. It appears to us that this set of experiment may be very important and that it is worth repeating it with a lot more care and quantitative measurements at every step that we did not carry out. The spatial intensity distribution is given by the square modulus of the two amplitudes. The unbalanced amplitudes in real experiments are indicated by a_1 and a_2. The variable phase delay along the spatial axis is given by τ.

$$I(\tau) = \left| a_1 e^{i2\pi\nu t} + a_2 e^{i2\pi\nu(t+\tau)} \right|^2 = A[1 + B\cos 2\pi\nu\tau] \quad (1)$$

The fringe visibility is degraded by the factor $B = 2a_1a_2/(a_1^2 + a_2^2); where, A = (a_1^2 + a_2^2)$. The traditional complex representation, while very convenient to derive a quantity proportional to the absorption of light energy, it hides a very important detection process, a short time that is required by the detecting dipole to respond to the filed and carry out the absorption process. This can be appreciated by re-writing the field amplitudes in real terms as $\{a_1 \cos 2\pi\nu t; a_2 \cos 2\pi\nu(t+\tau)\}$. Then the recovery of the RHS of Eq.1 will require accounting for a finite exposure time over a few cycles. The time integration is also physically justifiable because the EM field energy is always moving with the finite velocity, c.

$$I(\tau) \propto \int_0^T \{a_1 \cos 2\pi\nu t + a_2 \cos 2\pi\nu(t+\tau)\}^2 dt \approx A[1 + B\cos 2\pi\nu\tau] \quad (2)$$

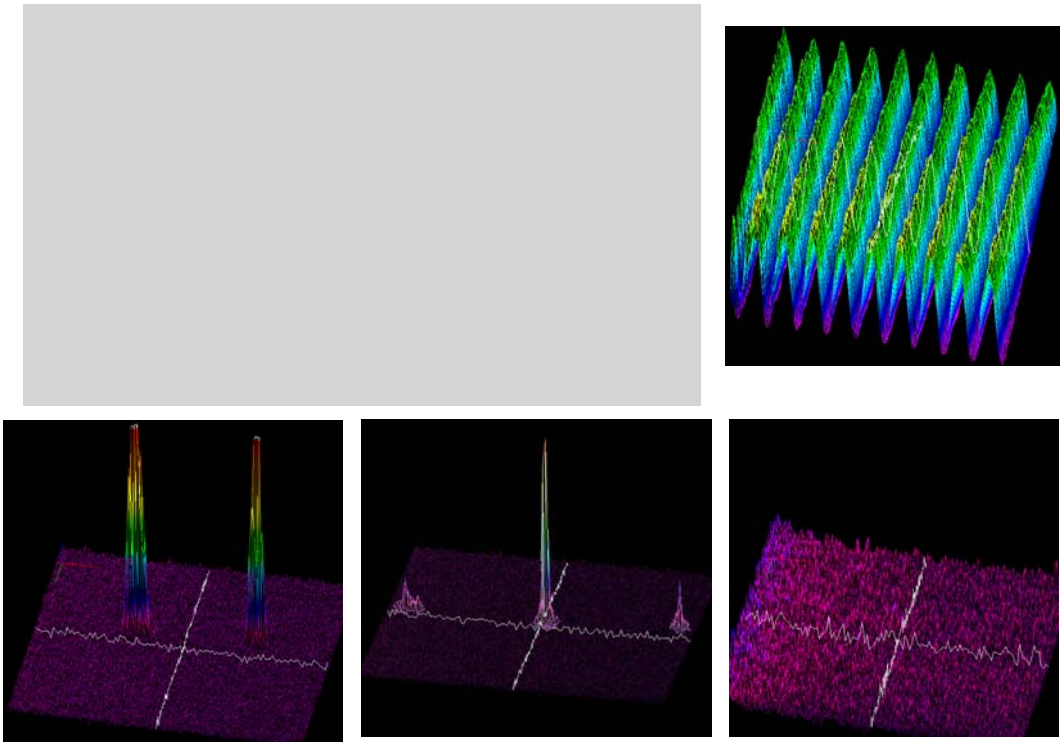

Figure 3. How is the energy re-distribution managed by intersecting light beams? Light does not interfere with light but detector array records local energy re-distribution when placed in the intersection. The transmitted beams appear to remain unperturbed even when active detection remains operational in the intersection! **Top-left:** Schematic diagram for a two beam holographic set up. The angle of intersection of the two beams was only a few degrees; it is greatly exaggerated in the sketch. **Top-right:** CCD camera record of the two beam fringes when the camera screen is symmetrically placed where the two beams intersect. It shows the local energy re-distribution **Bottom-left:** The two intersecting beams are focused on the CCD camera as two separate spots beyond their point of crossing. They are un-influenced by each other even though they crossed each other earlier. **Bottom-middle:** A hologram of the fringes (like top-right) was recorded and then replaced at the original intersection plane and illuminated by the beam-1 (assumed reference beam); the beam-2 was blocked. The CCD picture shows the focused spot for the directly transmitted reference beam-1 and two of the very weak, multiple diffracted orders from the hologram. [Notice apparent narrowing of the central light spot at low light level compared to the directly focused strong beams in bottom-left picture [see Ref.

6]. **Bottom-right:** Failed attempt to record diffracted orders when a long term, live exposure for a hologram was going on at the intersection of the two beams. The direct beams were care fully blocked off the camera screen. A very small amount of scattered light from the blocked direct beam can be seen on the left, but no diffracted orders.

5. Double-slit fringes by holographically recording one slit at a time

From the view point of classical physics, the conceptual model behind this experiment is quite standard; this is classical holographic interferometry! However, the paradigm of indivisible photon will encounter some conceptual challenge here because the photons are now required to have a pre-cognition of the existence of an obstruction behind one of the two slits before propagating through. Accordingly, the indivisible photons must statistically distribute themselves on the Fraunhofer (spatial Fourier transform) plane in (sinc^2)-form rather than in the form of a product, ($\cos^2$)(sinc^2). This has to be true because we do not let the obstruction touch the double-slit screen, which allows the photon to cross through the slit to determine that it cannot travel all the way to the Fraunhofer plane! The experimental results [22], shown in Fig.4, were recorded in two different ways. (i) By double exposure holography, which records both the single slit patterns separately and then reconstructs the fringes holographically by keeping both the slits blocked. (ii) By real time holography, which first records only one of the two slits, say slit-2, and reconstructs the double-slit pattern by real physical superposition of the signal arriving directly from slit-1 with the holographically reconstructed signal for slit-2 (while the actual slit-2 remains blocked). In our experiment we have used a 10mW He-Ne laser (~3.10^{16} photons/second). If indivisible single photon beam really existed ($3.1.10^{-19}$ W), can one really record such holograms? As per experiments of Panarella [6], a minimum of 3 to 4 photons equivalent of energy must be simultaneously present to trigger a single photographic grain to become "exposed" (chemically developable). Would these 3 or 4 photons go through a single slit as a single "clump" [6] and arrive at the right spot, or we need multiple photons arrive at the same spot but traveling through the two slits?

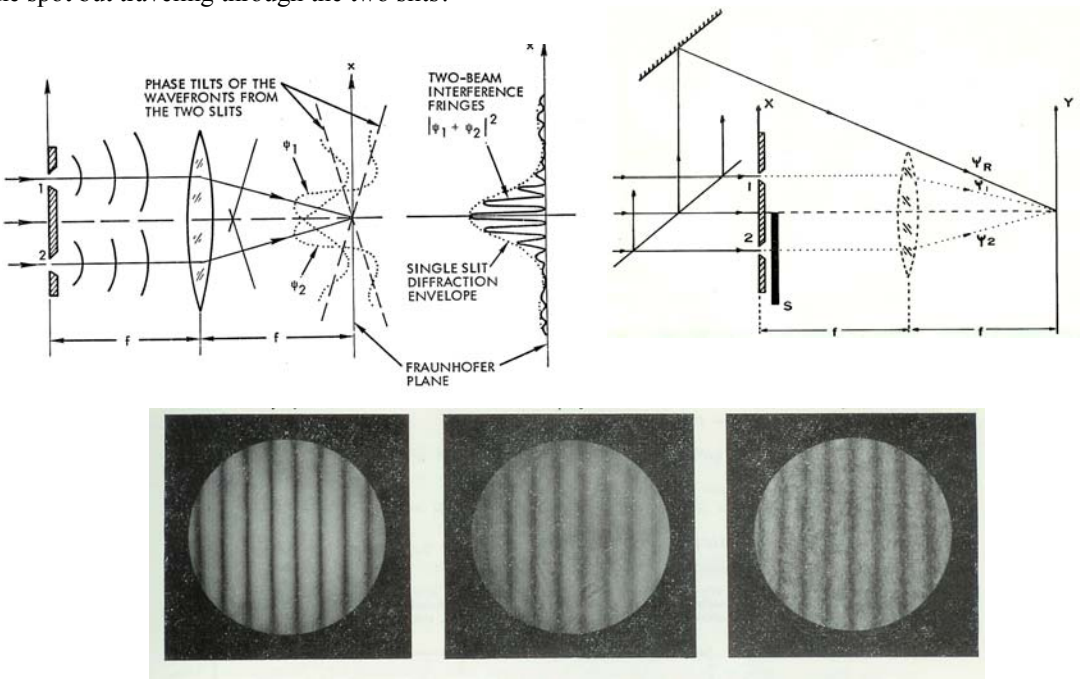

Figure 4. Signals from each one of the double slits can be recorded holographically one at a time and then the standard double-slit pattern can be reconstructed. **Top-left:** Geometric drawing of the classical interpretation as to how the signals from each slit arrives on the far-filed as a sinc-enevelope (spatial Fourier transform, FT, of each slit) with a finite tilt to generate the standard cosine fringes. **Top-right:** Holographic set up consistent with the sketch shown in top-left. **Bottom-left:** Direct record of the traditional double-slit pattern recorded at the FT (far field) plane. **Bottom-middle:** Holographic reconstruction of the double-slit pattern from a hologram that separately recorded the two single-slit patterns separately. The process is also known as double exposure holography. **Bottom-right:** Re-generating the double-slit fringes by real-time holographic interferometry – the signal from the slit-1 arrives directly on the hologram

and the signal from the slit-2 is reconstructed from the holographic record (actual slit-2 remains closed during this observation) [22].

6. Slowly moving double-slit fringes with a small Doppler shift on one slit

This is a conceptual experiment [23] designed to challenge the assertion that any attempt to determine which slit the light passes through will always destroy the formation of the interference fringes. The apparatus of Fig.5 consists of several separate smaller experiments that we routinely carry out in the laboratory. We have a pinhole at the center of the plane that can record the standard double-slit Fraunhofer pattern to allow the collection of light for high resolution spectrometric analysis by a Fabry-Perot interferometer (FP) operating in the fringe mode. When the double-slit is illuminated by a coherent beam carrying a frequency ν_1, one can observe the stationary cosine fringes on the Fraunhofer plane and the detector, named Ch.1, will register some count since the location has been chosen where the FP forms the fringe for frequency ν_1, with a constructive interference condition, $2d\cos\theta_1 = m\lambda_1$. If one switches the carrier frequency of the incident beam to be ν_2 [condition, $2d\cos\theta_2 = m\lambda_2$], then only the detector, Ch.2, will register counts. Let us now illuminate the double-slit with a light beam of frequency ν_1, but insert an acousto optic modulator behind the slit-1 that generates a frequency ν_2. The cosine fringes on the Fraunhofer plane will now be given by:

$$I(\tau) = \left| e^{i2\pi\nu_1 t} + e^{i2\pi\nu_2(t+\tau)} \right|^2 = 2[1 + \cos 2\pi\{(\nu_1 - \nu_2)t - \nu_2\tau\}] \tag{3}$$

These spatial fringes, as usual, defined by the spatial delay τ along the spatial axis [see Eq.1], are temporally modulated by the difference frequency, $(\nu_1-\nu_2)$, which is the traditional beat frequency. A pico second streak camera, covering a segment of the Fraunhofer plane can easily record these moving fringes as long as the beat frequency is in the domain of GHz or less. Now, if we pay attention to the detectors, Ch.1 and Ch.2, behind the FP spectrometer, we should be able to identify the ν_2-photons as those coming through the slit-2 after undergoing Doppler shift by the AOM and the ν_1-photons coming through the slit-1. This is not a "Gedanken" experiment. This is an experiment that does not challenge the current technology at all. Does it resolve the paradigm of "single-photon interference" unambiguously? No, but the purpose of this paper is to underscore that interference is always the result of real physical superposition more than one signal on a quantum detector carrying more than one phase information (traveling through more than one path). "Which way" can be determined without destroying the fringes, if we use a fast enough detector.

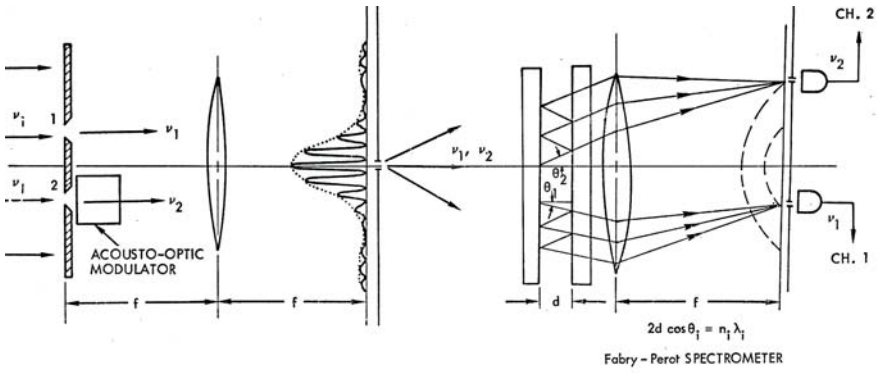

Figure 5. It is possible to determine that the double slit pattern is actually due to the superposition of two signals traveling separately through each slit and arriving at the detector plane with different relative phase delays. In the above experiment the identifier is a Doppler frequency shifter, ν_1 to ν_2. This makes the double-slit fringes at the Fraunhofer plane spatially move through a point at a rate of the beat frequency, $\delta\nu = (\nu_1-\nu_2)$. A high resolution spectrometer behind the Fraunhofer plane can separately count the photons corresponding to each frequency and the counting will show precise coincidence. A spatial segment on the Fraunhofer plane can be intercepted by a fast Streak Camera to record the fringes, albeit moving spatially [23].

7. Spatial localization of Mach-Zehnder fringes using polarization

This experiment, actually carried out in our laboratory, exploits the quantum properties of the detectors that the same dipole cannot execute two orthogonal undulations at the same moment in the linear domain. Since light does not interfere with light, the absence of fringes (local re-distribution in detected energy) due to the superposition of orthogonally polarized light beams, has to be attributed to the intrinsic properties of the detectors, not that of light. The Fig.6 gives the schematic diagram of the Mach-Zehnder interferometer (MZ), the recorded fringes and the schematic representation of the presence and absence of spatial fringes over the screen. Good visibility fringes are recorded when the state of linear polarization is deliberately set to be parallel. Then, turning the two parallel polarizers in the two arms of the MZ by 45^o in the opposite directions, the fringes are completely destroyed. But, insertion of a linear polarizer, exactly bisecting the 90^o restores the interference fringes. To underscore the locality of interference (detectors carry out the superposition process), we deliberately made the fringe restoring polarizer physically smaller than the total beam size. Only behind the polarizer the two transmitted beams are now polarized parallel and the detecting dipoles now can oscillate either strongly (bright fringes) wherever the superposed two E-vectors are in phase, or they do not oscillate (dark fringes), wherever the superposed two E-vectors are out of phase. Outside the polarizer on the detector screen, the dipoles can respond to either one of the E-vectors, not to both, irrespective of their phases; accordingly, the energy absorption is uniform without modulation. Mathematically, this is traditionally taken care of by the vector product of the dipole undulations:

$$I(\tau) = \left|\vec{d}e^{i2\pi\nu t} + \vec{d}e^{i2\pi\nu(t+\tau)}\right|^2 = 2[d^2 + \vec{d}\bullet\vec{d}\cos 2\pi\nu\tau] \qquad (4)$$

Here $\vec{d}$ is the electric field induced dipole vector. The interference cross term vanishes when the two orthogonal fields (linear or circular polarization) try to stimulate the same detecting dipole at the same instant.

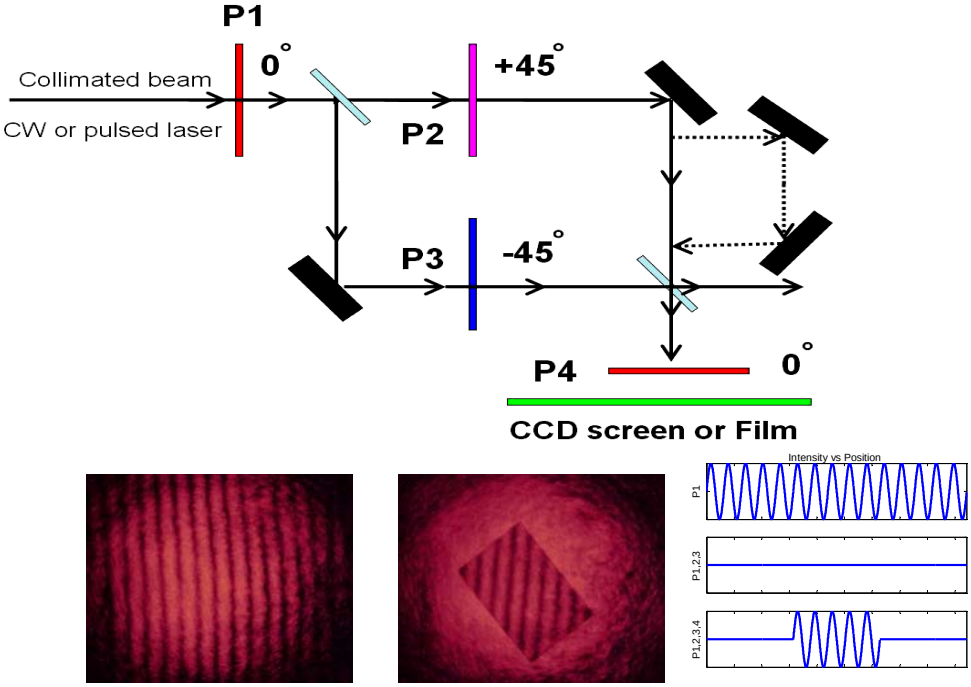

Figure 6. The locality of Mach-Zehnder (MZ) fringes are underscored using a small piece of Polaroid in front of the detector screen when the two superposed MZ beams are deliberately made orthogonally polarized. **Top:** Schematics of the MZ interferometer with four polarizers to assure proper manipulation of the state of polarization while keeping the amplitudes of the two beams very closely equal. **Bottom-left:** The two states of polarizations are parallel in the two MZ arms. **Bottom-middle:** The two states of polarizations are orthogonal to each other in the two MZ arms indicating complete loss of fringe effect, except in the middle of the screen where a linear polarizer is placed right on the detector plane bisecting the two orthogonal directions. **Bottom-right:** Three different depiction of the intensity record on the detector plane. The top curve describes the situation shown in the picture identified as the 'Bottom-left'. The straight middle curve depicts the situation for the picture "Bottom-middle', but outside the Polaroid. Its bottom curve indicates the re-appearance of the fringes just behind the small Polaroid of the picture identified as the "Bottom-middle'.

8. Spatial and temporal localization of Mach-Zehnder fringes by superposing a train of translated pulses with separate beam diameters.

The purpose of this experiment is to raise further doubts on the concept of non-locality of photons when one can easily confine the energy of electromagnetic fields, both in space and in time, simply by using optical components and modulators. This is another experiment not yet carried out but quite feasible with the standard off-the-shelf technologies. Consider the MZ of Fig.6 ('Top') illuminated by a train of square pulses, derived from a stabilized CW laser by a high speed amplitude modulator. The pulses can be combined at the output of the MZ with variable temporal delay (i) either to exactly match the simultaneous temporal superposition of the pulses from the two arms on the detector, (ii) or, to completely mismatch their time of arrival on the detector. When the pulses are time synchronous on the detector, one can record perfect fringes with simple slow detectors like photographic plate that integrates the signal over the entire period of exposure. Remember that due to delay, this interference is due to simultaneous presence of different pulses, and hence due to superposition of different time delayed photons. When the pulses are exactly asynchronous (never simultaneously present together on the detector), there will be uniform intensity record but no fringes. The cross term between the two amplitudes is absent because the detector dipoles could not experience the simultaneous stimulation by the two amplitudes at the same time. This point also underscores again that the effect of superposition becomes manifest only through the participation of the detector dipoles.

If one now drastically reduces the photo count by reducing the input beam energy, the appearance of the fringes will require long time integration. Does this classic "click-by-click" integration to build up the fringe pattern imply the indivisible, non-local photons could anticipate the arrangement of the entire apparatus to arrive at the right location of the potential fringe? This cannot be right because now the photons in the time domain has been confined within the pulse width and one can validate that the "clicks" can be registered only within this allowed periodic time intervals. Further, one can choose an interferometer many nano seconds long while the photons can be kept confined within the pulse width of a few pico seconds. The implication is that the paradigm of "non-local photon" is self-contradictory.

If the beam size in one of the two MZ arms is telescoped down to a smaller size than the other one, the fringes will be visible only over the smaller beam size; the out side will register energy without fringes. This spatial confinement is some what similar to the experiment of Fig.6 where the fringes were restored just behind a small polarization parallelizing element.

If the MZ beams are collimated and are of exactly the same amplitude and physical shape, and further, if they are superposed on the final beam splitter surface at an angle such that they create perfect co-linearity between the transmitted beam from one beam with the reflected counter part of the other beam, then the total energy contained in both the beams will be re-directed only in one of the two allowed directions, based on the relative phase conditions. Again, this energy re-direction can take place only through the mediation of the dipoles on the surface of the beam splitters and the derivation was done more than a century ago using Lorentzian dipole model and Maxwell's equations, without the advantage of Quantum Mechanics.

9. Summary

We do not see light without the mediation of other materials. Light beams do not interfere with each other without the mediation of interacting materials (detectors). It is logically inconsistent that we should be able to produce a new phenomenon of interference between light beams without the mediation of detecting materials simply by reducing the intensities to arbitrary low values. So, the paradigm of non-local and indivisible single photon producing interference effect should be carefully re-visited [3-8]. Even the use of Bell's inequality to justify non-locality has been logically questioned [24]. We have presented a number of actual and potential experiments to underscore that the effects of superposition of light beams can become

observable only when some appropriate detector is capable of simultaneously responding to all the superposed fields arriving through all the allowed paths. All the fields must also be physically present simultaneously on the detector (both in space and in time) so the detector has the causal opportunity to act on all of them (or be simultaneously influenced by all of them) and register the effect of superposition. Photons definitely contain sharply defined quantum of energy $\Delta E = h\nu$ at their birth. But, how do they evolve as they propagate? It is worth modeling their evolution (propagation) as classical wave packets following the classical diffraction theory that allows them to evolve collaboratively (superposition principle) into new wave packets by sharing energies in space and time such that their energy loss by diffraction is minimized in their long journey! Without first finding validated failure of classical, causal diffraction theory, it is premature to accept a non-causal model for photons that is simultaneously indivisible and non-local.

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