Optik xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Experimental observations of redistributed energy in wave interference

C.K. Gamini Piyadasa*

Department of Physics, University of Colombo, Colombo 03, Sri Lanka

ARTICLE INFO

Article history:
Received 16 May 2011
Accepted 20 September 2011
Available online xxx

PACS:
42.25.Hz
42.25.Kb
41.20.Jb

Keywords:
Wave theory
Interference
Coherent
Energy re-distribution

ABSTRACT

Attempts to explain the redistribution of energy in interference has been done from time to time, under two of the most accepted theories, wave and quantum; however its mechanism still lacks clear interpretation. In this study, a new experiment has been designed and conducted to observe the redistributed energy in wave interference. Experimental observations on the redistributed energy that occurs in two interfering coherent waves are presented. Re-distributed energy at a certain region, (single bright fringe) in space due to interference of two waves was isolated at a plane and measured at a distant plane away from the isolated plane. The measured energy distribution of the isolated interference pattern was compared with the resultant calculated from the two individual interfering components based on wave theory. The calculated resultant due to the two individual components does not tally with the experimental observed pattern. Hence, the outcome of this experiment is in disagreement with the expected predictions as per the wave theory.

1. Introduction

The energy transportation in space was a question ever since mankind started to discover and understand the nature. The inquisition began with light, as it is the most perceptible phenomena of nature that people were amused of. As light is a conveniently observable entity, optics emerged as one of the foremost sciences in medieval times. Christian Huygens (1629–1695) in 1690 postulated light as a progressive wave and it is the most widely accepted theory till date. As per the wave theory, light transfers energy in the form of a wave where the energy is thinly distributed in wave fronts [1]. He further said that at any given instant, each point of a wave front is the origin of a secondary wave, which propagates outwards in all directions with a speed equal to the speed of propagation of the waves. The secondary waves then combine to form a new wave front. Huygens model explains geometrically some of the fundamental optical observations successfully and it served as the basis of one of the most important historical and fundamental experiments, the Young's double slit experiment [2].

A contemporary of Huygens, Isaac Newton proposed a different theory for the nature of light. He described light as consisting of very infinitesimal particles emitted from shining objects, which were named as corpuscular [3]. James Clerk Maxwell (1831–1879) described visible light as a form of electromagnetic (EM) energy. He further said that, at a point in space, an EM wave can be specified by two vectors, the electric field $\vec{E}$ and the magnetic field $\vec{H}$ which are perpendicular to each other and normal to the direction of propagation. Their space and time derivatives are interrelated by four equations in vacuum termed Maxwell's equations [4]. At the beginning of the twentieth centaury, Planck [5], Einstein [6] and Bohr [7] considered that EM waves consist of discrete amounts of energy, called photons or quanta (packets) of energy. In 1924 De Broglie [8] postulated that EM waves have both particle and wave properties,which we refer today as the wave-particle duality. Even though, the particle nature describes some of the observed phenomenon in nature, such as photoelectric effect, most of the observations in the physical world related to the energy spectrum could be explained by Maxwell's electromagnetic theory of wave nature.

2. Theoretical background

A plane wave moving in the x direction is given by $(\partial^2\vec{E}/\partial x^2) - (1/c^2)(\partial^2\vec{E}/\partial t^2) = 0$, where the speed of light $c = (1/\sqrt{\mu_0\varepsilon_0})$, and μ_0 being the permeability and ε_0 being the permittivity in free space. The monochromatic solution to this wave equation has the form $\vec{E} = \vec{E}_0 e^{j(\omega t+\phi)}$ where $\vec{E}_0$ is the maximum amplitude, ω is the angular frequency and ϕ is the phase angle. This is true for all EM waves. One of the key features of wave nature is the superposition. The superposition of two waves $\vec{E}_1 = \vec{E}_{10} e^{j(\omega t+\phi_1)}$ and $\vec{E}_2 = \vec{E}_{20} e^{j(\omega t+\phi_2)}$ is given by $\vec{E} = \vec{E}_1 + \vec{E}_2 = \vec{E}_{10} e^{j(\omega t+\phi_1)} + \vec{E}_{20} e^{j(\omega t+\phi_2)}$ where $\vec{E}_{10}$, and $\vec{E}_{20}$ are maximum amplitudes and, ϕ_1 and ϕ_2 are the phases of the respective waves. The intensity, *I*, of a wave is defined

* Corresponding author. Fax: +94112584777.
E-mail address: gamini@phys.cmb.ac.lk

0030-4026/$ – see front matter © 2011 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2011.09.026

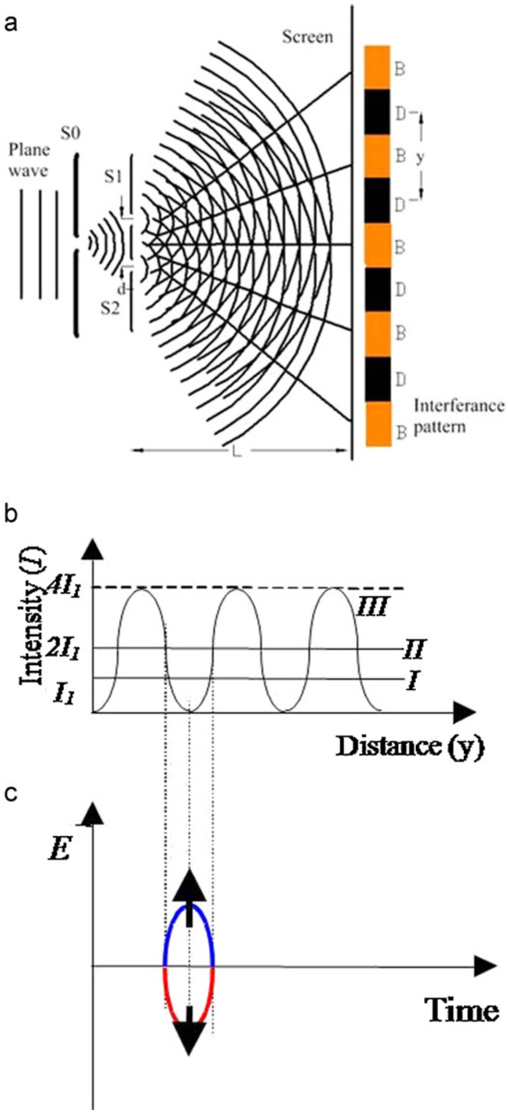

Fig. 1. (a) Young's double slit experiment and its energy re-distribution. In this, S_0 is a single slit and S_1 and S_2 are double slits. When a plane wave is incident on the slit S_0 it will act as a primary point source and S_1 and S_2 as secondary point sources of light. B indicates bright zones and D indicates dark zones. The distance between two dark (or bright) fringes in interference pattern is y, λ is the wavelength of the incident wave, L is the distance between the plane of the slits and the screen and d is the distance between the two slits. (b) Intensity distributions produced by light beams: a single light beam (I), double incoherent light beams (II) and double coherent light beams (III) and (c) equal and opposite $\vec{E}$ vectors of two beams produces a null at interference pattern.

as the time average of $\vec{E}$ and hence $I \propto \langle \vec{E} \rangle^2$. The intensity (average power per unit area) is the measure of energy. So the resultant intensity (I) of the two waves with intensities I_1 and I_2 is given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\phi_1 - \phi_2) \tag{1}$$

If $I_1 = I_2$ and $\phi_1 = \phi_2$ (zero phase difference) then $I = 4I_1$ (condition (1)). Whenever the phase difference is π the intensity becomes zero then $I = 0$ (condition (2))

Young's double slit experiment [2] was one of the landmarks in science that has been carried out to verify the wave nature of light (Fig. 1(a)). It describes the superposition of two coherent light waves; intensities of the waves in the same phase (in-phase) add up as in condition (1) and produce bright region (constructive interference) and waves that are π out of phase (condition (2)) produce dark regions (destructive interference). These regions are also referred to as "maxima" (bright or maximum intensity) and "minima" (dark or zero intensity) respectively (see Fig. 1(a)).

If λ is the wavelength, d is the distance between the two slits and L is the distance to the screen from the slits, then the distance to the mth bright region from the central line of the slit is given by the following approximate mathematical relation (see Fig. 1(a))

$$y \approx \frac{m\lambda L}{d} \tag{2}$$

where $m = 0, 1, 2, \ldots$. Eq. (2) is an important result applicable to all interference effects where two primary, coherent, monochromatic sources giving out nearly parallel beams and predicts the energy redistribution in space. Fig. 1(b) shows this energy (intensity) redistribution across an interference pattern on a screen. A single beam of light gives a uniform distribution of intensity, I_1, throughout the screen as shown in curve I of Fig. 1(b). Two non-coherent beams of equal intensities I_1 would yield a uniformly illuminated screen with intensity $2I_1$ (see curve II in Fig. 1(b)). If the two waves are coherent, or in other words, the two beams have a phase relationship that satisfies the condition for interference in Eq. (2), they form alternative maxima and minima, hence a re-distribution of energy. If initial amplitudes of the two coherent beams are equal, then the maxima are four times the intensity of the individual contribution ($4I_1$) as shown in curve III of Fig. 1(b). However, the area under interference curve III is equal to that of the curve II, hence energy is conserved.It is known that the energy of an EM wave at any point is a measure of the rate of energy flow per unit area at that point; the direction of the energy flow is perpendicular to $\vec{E}$ and $\vec{H}$; i.e. in the direction of the vector $\vec{E} \times \vec{H}$ (Poynting vector, John Hentry Poynting (1852–1914)). Furthermore, the superposition theorem predicts the resultant at a given point in space when two or more EM waves are present at that point.

The following can be inferred from the wave theory,

(i) Energy of an EM wave at any point in space is associated with the electrical vector $\vec{E}$ of that wave at that point and is proportional to $(1/2)\varepsilon_0 E_0$ in magnitude.
(ii) The resultant of two or more EM waves at any given point in space depends only on the $\vec{E}$ and $\vec{H}$ field vector magnitudes and the phase relationship of those waves at that point. However this resultant would not be affected by the past encounters of the same waves and moreover, the interference in the zone of interaction will not cause any sustaining alterations in the original waves in their further propagation. In other words the interference of two waves at a location in space will not cause any impregnation of interaction of the incident (i.e. interference) in any of the individual waves in a way that they can be observed at a future time at another point in space. This leads to the following paradox with the existing wave theory.

If we consider nodes in an interference pattern, to achieve destructive interference or zero intensity, the $\vec{E}$ vectors of the two waves should be equal and opposite at that particular point at any time (Fig. 1(c)). In other words that can be considered as a Tug of War! If the two opposing forces are equal then there is no resultant movement in the rope. When both beams are coherent and identical in amplitudes and phases, maxima will be formed of which the intensity is four times that of an original wave (referred as condition (1)). Although, this is explained mathematically, it seems that the energy of minima has been shifted towards maxima because it is shown (experimentally as well – [Ref. [10] section. 2.0]) that the total energy is conserved in the interference. Since the two $\vec{E}$ vectors with equal amplitudes and a π phase difference have to be present at minima to ensure zero intensity at those regions, the classical wave theory leads to an important riddle; whether the energies dissociate themselves from their $\vec{E}$ vectors at such minima.

Please cite this article in press as: C.K.G. Piyadasa, Experimental observations of redistributed energy in wave interference, Optik - Int. J. Light Electron Opt. (2011), doi:10.1016/j.ijleo.2011.09.026

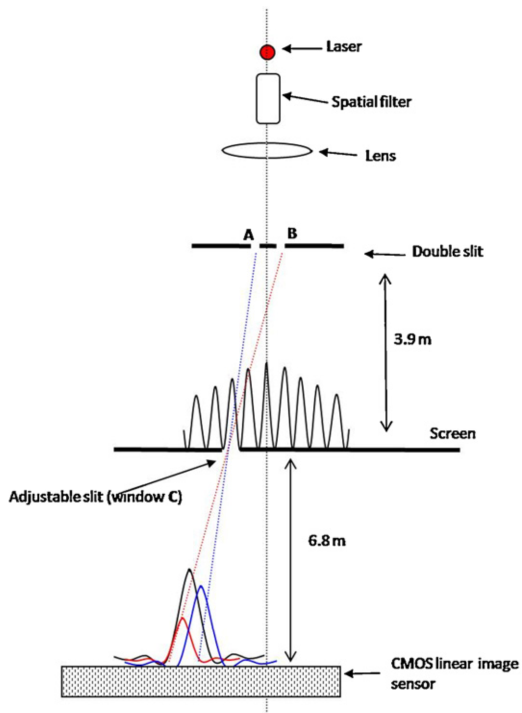

Fig. 2. The experimental set-up. The He–Ne laser, spatial filter and lens combination provide a clean parallel laser beam for the double slit (slits A and B) experiment. The distance between the slits is 1.46 mm (center to center) and the slit width is 0.2 mm. Slits are constructed in such a way that each slit can be covered without disturbing the other. A variable knife-edge slit, *C* is used to select a single peak from the interference pattern. The distance between double slit and the window C is 3.9 m. One inch CMOS linear image sensor is used to record the intensity at the observation plane at a distance of 6.8 m from the window C. Intensity profiles are recorded for three different situations; slit A open (i.e. slit B close), slit B open (i.e. slit A close), and both slits open.

The redistribution of energy in interference has been done only in a few studies [9,10]. It has been observed in [10] that the energy re-distribution profile encountered in the region of interference by two coherent waves persists in the individual waves as they leave the region of interference. This observation contradicts wave theory interpretation. This ambiguity in redistribution of energy has been confirmed experimentally in this attempt.

3. Experimental set-up

As shown in Fig. 2, a He–Ne laser, a spatial filter and a lens combination provide a clean parallel laser beam to the double slit (slits A and B) experiment. The double slit was installed vertically to produce vertical bright fringes.

The separation between the slits was 1.46 mm (center to center) and the slit width was 0.2 mm. Slits have been made in such a way that each slit can be covered without disturbing the other. A variable vertical knife-edge slit was used to select a single peak from the interference pattern at the screen. At the plane of observation, 1 in. CMOS linear image sensor (Hamamatsu 10453-1024 pixel – each 25 μm with adjustable exposure time) was placed to record the output beam coming out of the adjustable single slit (window C) in the horizontal plane to detect the entire line of energy redistribution. In this particular set-up, the width of the window C was 2.2 mm. The wavelength of the He–Ne laser light is 632.82 nm in air. The window C was set to select just one peak at a time. The best available precautions were taken to align the window edges with the center of the dark regions besides a selected bright peak. The intensity data were converted into an ASCII code and then stored in a data file and later analyzed by Kaleida Graph (version 3.6) computer software.

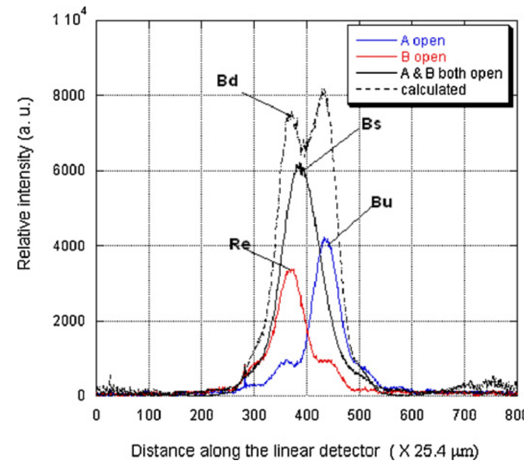

Fig. 3. The intensity recorded at the CMOS detector array for three different experimental arrangements: Only slit A is open – the blue curve (*B*), only slit B is open – the red curve (*Re*) and both slits, A and B are open – the black curve (*Bl*), calculated curve according to the superposition theorem of waves from slits A and B – the dotted black curve (*Bd*). The intensity is in arbitrary units and the horizontal axis is in μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Intensity profiles were recorded at the detector plane for three different situations; slit A opens (i.e. slit B closes), slit B opens (i.e. slit A closes) and both slits open. The intensity measurements were taken along several horizontal lines at different vertical positions and each measurement (average of 10) was repeated three times (in different order) to verify the reliability and consistency of the data obtained. Exposure time of the CMOS detector was kept fixed throughout the experiment.

4. Results

Diffraction patterns were observed for each slit, slit A and slit B, at the plane of the screen (Fig. 2) when the two slits were opened one at a time. These diffraction patterns are relatively large compared to that of the dimensions of the window C (nearly flat profile, refer Fig. 5). There is another diffraction pattern that occurs in the plane of the detector due to the corresponding diffraction pattern in the screen (the energy transferred through the window C). Fig. 3 shows two diffraction patterns from slit A (the blue curve symbolized by *Bu*) and slit B (the red curve symbolized by *Re*) observed one at a time in the plane of the detector. When both slits A and B are open, a bright fringe occurring in the interference pattern at the screen will be selected by the window C and transmitted to the detector plane. The intensity profile observed in this case is depicted by the black curve (symbolized by *Bs*) in Fig. 3.

5. Analysis

The two waves from slits A and B, pass through the window C at a certain angle due to the geometry of the experimental set-up and produce two diffraction patterns (when slits A and B open one at a time) at the plane of the detector as in Fig. 3. The amplitude difference in the two diffraction patterns is due to the difference in the optical path from the double slit to the detector. When the both slits are opened, an interference pattern will be produced on the screen and one bright fringe selected by the window C will be transmitted towards the detector. As per the "wave theory of interference", the resultant intensity pattern at the plane of the detector could be reproduced by the vector addition of the two individual components of $\vec{E}$ fields, produced by each wave. Furthermore, at the screen, the individual fields ($\vec{E}$ or $\vec{H}$) of the waves should exist

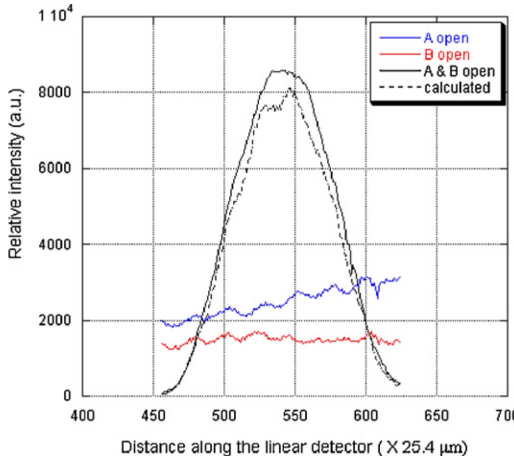

Fig. 4. The reconfirmation of the methodology used to obtain the phase information for the simulation. The sections of two diffraction patterns on the plane of observation when slits A and B are open individually are shown by the blue and red curves respectively. The black curve shows the interference peak when both slits, A and B are open. The black dotted line is the curve calculated using the data of the two segments. The intensity is in arbitrary units and the horizontal axis is in μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the zone of interference (screen). The resultant effect of superposition modifies the energy distribution at the window *C*. When *C* is open, the two waves reach the final plane of observation (detector). According to the theory of superposition, the vector addition of the two intensity profiles (*Bu* and *Re*) should be same as the observed resultant curve *Bs*.

To construct the resultant from the individual intensity distributions, we need to know the amplitudes and the phase differences at each point (Eq. (1) is employed). The amplitudes at each point are already available from curves *Bu* and *Re*. As per the wave theory (or superposition theorem), it is possible to obtain the phase information from the experimentally observed resultant intensity curve (*Bs* in Fig. 3). Here we can assume that the phase differences of two interfering components (diffraction patterns *Bu* and *Re*) become zero at the central maximum of the resultant peak (*Bs* in Fig. 3) and it is $\pm\pi$ at the two adjacent minima on either side of *Bs*. Assuming these conditions, it is possible to re-construct the resultant as per Eq. (1). The simulated curve is shown in Fig. 3 by the dotted black curve, *Bd*. Interestingly the calculated intensity pattern (*Bd*) is not in agreement with the observed pattern (*Bs*).

The method used to obtain the phase relation in two diffracting waves is reconfirmed using the intensity measurements of an arbitrary peak in an interference pattern. Fig. 4 shows the segments of two diffraction patterns (in blue and red colors) in the plane of observation when slits A and B are open separately. The black curve shows the observed interference peak when both slits, A and B are open. The dotted curve is the calculated curve by using the data of fractions of those two diffraction curves in Eq. (1). The reconstructed curve (black dotted in Fig. 4) shows a very close correlation (correlation factor 0.998) to the experimentally observed curve. It further confirms that the assumption that we made in the original problem is reasonable to be adopted.

In order to further verify the above discussed disagreements between the observed and calculated intensity patterns and also to justify the assumption made on the selection of phase angles, the following procedure (Mathematica 5.0, Wolfram research) was followed. The resulting intensity curve was obtained by superimposing two theoretically derived intensity patterns (similar in profile to the experimentally observed intensity curves at the detector from slits A and B separately) with varying amplitudes and phase relations.

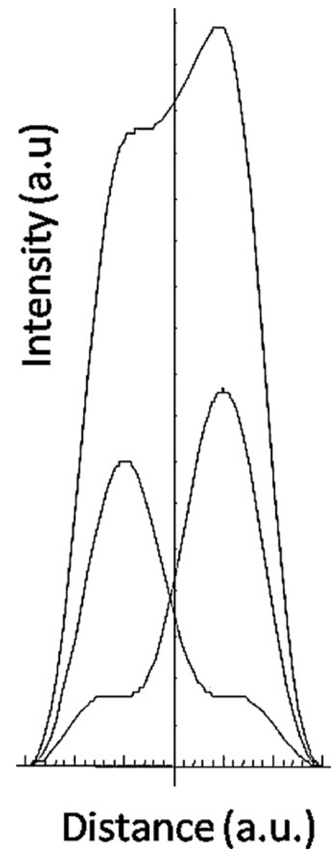

Fig. 5. The simulated curves according to the observation made in the experiment. The resulting intensity curve was obtained by superimposing two intensity patterns similar to the observed data with varying amplitudes and phase relations. The outcome shows that the resulting interference curve always encloses the peaks of the curves of component intensity patterns.

The outcome of this theoretical simulation shows that the resulting interference curve always encloses the peaks of the curves of component intensity patterns. Such a theoretically simulated set of curves is given in Fig. 5. This theoretically simulated curve in Fig. 5 is similar to the simulated curve obtained with experimental data in Fig. 3 (*Bd*). In contrast to the outcome of these simulations, it can be clearly seen that the intensity pattern of a component distribution (*Bu*) is not enclosed in the envelope of the resultant curve, *Bd* in our experimental observations (Fig. 3).

The resolution of the detector system which is ±25 μm is negligible as compared with the measurements taken in the experiment such as the separation between envelope of the resulting curve (*Bs*) and the outside peak (*Bu*) of the component wave (about 1500 μm). These observations suggest that the results are not in agreement with the predictions made under the wave theory (or superposition theorem).

6. Conclusion

Some lapses of knowledge in the interpretation of energy in interference are reported in this paper with the following highlights.

- As mentioned in energy re-distribution, there is an unexplainable observation at destructive interference (whether the energies dissociate themselves from their $\vec{E}$ vectors at such minima) which leads to a serious question in the wave theory or/and superposition theorem.

- The second observation made with the re-distributed energy and its behavior afterwards also raises the same question. The modified energy distribution at the window C in the screen seems propagating further without altering its energy profile in the absence of an external influence. This is not the result expected from the wave theory and superposition theorem.

If both are true, the explanation of interference in the wave theory is in jeopardy. It should not be forgotten that the interference is the foremost fundamental concept available to prove the wave theory.

Acknowledgments

The author gratefully acknowledges financial support by the National science foundation in Sri Lanka (Grant no. NSF/Scientist/2007/01 and G. Gwinner of the Department of Physics and Astronomy, University of Manitoba, Canada and the Department of Physics, University of Colombo for providing the laboratory facility for carrying out this work. The author also acknowledges G. Roy and V. Spicer in University of Manitoba for their assistance during the first phase of this experiment. Special thanks goes to GS Palathiratne and GAC. Gomes for their helpful comments and critical reading of the Manuscript.

References

[1] C. Huygens, Traite de la Lumiere, Leiden, Van der Aa, 1690.
[2] T. Young, On the theory of light and colours, Philosophical Transactions of the Royal Society of London 92 (1802) 12–48.
[3] L. Newton, Opticks or a treatise of the reflexions, refractions, inflexions and colours of light, Royal Society of London (1704).
[4] J.C. Maxwell, A dynamical theory of the electromagnetic field, Philosophical Transactions of the Royal Society of London 155 (1865) 459–512.
[5] M. Planck, Entropy and Temperature of Radiant Heat, Annalen der Physik 1 (4) (1900) 719–737, On the law of distribution of energy in the normal spectrum, Annalen der Physik 4 (1901) 553.
[6] A. Einstein, Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, Annalen der Physik 17 (1905) 132–148.
[7] N. Bohr, H.A. Kramers, J.C. Slater, The quantum theory of radiation, Philosophical Magazine 6 (47) (1924) 785–822.
[8] De Broglie, Recherches sur la théorie des quanta (Researches on the quantum theory), Thesis, Paris, 1924.
[9] C. Roychoudhuri, The nature of light: what is a photon? in: Proceedings of SPIE, the International Society for Optical Engineering, vol. 5866, 2005, pp. 135–146.
[10] C.K.G. Piyadasa, Redistribution of energy in electromagnetic wave interactions – interference of electromagnetic waves; a different approach Sri Lankan Journal of Physics 6 (2005) 51–64.