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Some Considerations on the Speed of Light

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Abstract
In this work, based on the proposed new refined definition of light in [1,2], which reveals the physical nature and properties of this object of matter at the level of photons, some considerations are put forward about the speed of light. According to these considerations, the propagation speed of individual photons in the vacuum of various components of the light spectrum, as a function of multiplicatively related two physical quantities - the wavelength and frequency of photons, remains a constant value. At the same time, the measured value of this speed by the measuring device* for various components of the light spectrum is noticeably, and in the ultraviolet range, significantly different. In the visible region of the light spectrum, this difference reaches a value of 1.9; in the infrared range - up to a value of 2.1; in the ultraviolet range - up to a value of 80; and in the full spectrum of light - up to a value of 320.

Keywords: Light, Speed of light, Speed of a single photon, Length, Wave component of the speed of a single photon, Frequency component of the speed of a single photon.

Introduction

We start this work with a brief note about research on measuring the speed of light, which is the most important parameter of light from a practical point of view and has about three and a half centuries of history [3]. In 1676, the Danish scientist O. Romer carried out such a measurement for the first time using the method called measuring the speed of light by the delay of the eclipses of Jupiter's satellites. Using this method, he found that light travels at a speed of 230,000 km/s.

Further, this research was carried out in two directions. In the first one, the method of light modulation by a gear, first developed and implemented in 1849 by N. Fizeau, was continued by his followers A. Cornu in 1873 and 1874, Jung and Fobs in 1875. In the second one, the method of rotating mirrors and prisms, first carried out in 1862 by L. Foucault, was continued by his follower A. Michelson.

According to these studies, the following values of the speed of light in airless space (vacuum) were obtained:

- 324,140 km/s (according to the method of Fizeau, 1849);
- 298,500 km/s (according to the improved method of Fizeau by Cornu, 1873);
- 300,330 km/s (according to the improved method of Fizeau by Cornu, 1874);
- 301,382 km/s (according to the improved Fizeau method by Young and Fobs, 1881);
- 298,000 km/s (according to the method of Foucault, 1862);
- 299,954 ± 50 km/s (according to the improved method of Foucault by Michelson, 1875).

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* The measured speed of light is defined as the value of $L/(t_2-t_1)$, where L is the distance between the light source and the light receiver, t_2-t_1 is the difference between the moments of the reception of the first photon by the photodetector of the measuring device and the emission of this photon by the light source, for different components of the light spectrum.

The indicated discrepancies between the results in those years gave reason to suspect

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whether the speed of light does not depend on the nature of the emitted light change along with it.
In 1872, Miller suggested that the speed of light may be dependent on the intensity of the light, and Phobs and Jung in 1881 reported that they noticed different speeds with different colors. However, these assumptions were not supported by the majority of the physicists.
Note that most measurements of the speed of light (except for the measurements of Phobs and Young) were carried out for white light by fixing the times of light's exit from the source and its detection by the measuring device and measuring the distance between the light source and the receiving device.
By now, the scientific and educational literature uses the rounded data: 299,792,458 ± 1.2 m/s = 300,000 km/s for the speed of light [4].
Readers of the International Journal of Modern Physics B are aware that a new refined definition of light was proposed in [2], according to which *"A light beam is a continuous (one after an arc with a certain repetition rate) stream of corpuscles (particles called quanta or photons) that have a certain mass, energy, momentum, angular momentum, and have the properties of an electromagnetic wave. This beam consists of many corpuscles - waves, i.e. wave trains and packets having different wavelengths, amplitudes, polarization planes, different in phase and propagating with a speed of $3 \cdot 10^{8}$ m/s in vacuum. in vacuum. These wave trains and packets propagate rectilinearly in homogeneous media and nonlinearly in inhomogeneous media, depending on the change in the refractive index n due to the bulk properties of the medium and the photon wavelength in these media at a speed of $(3 \cdot 10^{8}/ n)$ m/s. In other words, when discussing the properties of light, one should focus on the dual - both corpuscular and wave properties of photons, i.e. particles of light, not light in general."*
This definition allows revealing the physical nature and properties of light at the level of photons - particles (corpuscles) that have the property of an electromagnetic wave. According to this definition, individual photons of various components of the light spectrum, as we see, differ not only in amplitude, phase, plane of polarization, but also in mass, energy, momentum, angular momentum, etc.

Problem Statement

In the light of the above, some questions arise regarding the propagation speed of individual photons of various components of the light spectrum.
This paper is devoted to the presentation of some considerations on these issues.

Solution

When considering this issue, we proceed from the following assumption: atomic-molecular processes in natural and artificial sources of light radiation occur in such a way that the individual components of the light spectrum are independent of each other.
Obviously, the speed of a single photon in a vacuum is determined by the following relation:

$$V_{single\ ph.} = \lambda/T = \lambda/(1/\nu) = \lambda \cdot \nu, \quad (1)$$

where T is the period corresponding to the wavelength λ, ν =1/T is the photon frequency. It follows from relation (1) that the speed of a single photon due to a proportional change in the period T (reciprocal to the frequency ν) with a change in the wavelength λ s constant for all components of the light spectrum, that is, being a universal constant, with its value, according to the theory of Maxwell [5]:

$$C = 1/(\epsilon_0 \cdot \mu_o)^{1/2} = 3 \cdot 10^8 \text{ m/s}, \quad (2)$$

where ϵ_0 is the dielectric constant, μ_o is the vacuum magnetic susceptibility, numerical

values, numerical values of which are $1/(4\pi\cdot 9\cdot 10^{9})$ F/m and $4\pi\cdot 10^{-7}$ H/m, respectively.
Let us write relation (1), for example, for the components of the visible light spectrum:

$$V_{single\ ph.} = \lambda_{red}/T_{red} = \lambda_{oy}/T_{oy} = \lambda_g/T_g = \lambda_{bc}/T_{cb} = \lambda_v/T_v = C = \text{const.} \quad (3)$$

Based on relation (1), we rewrite relation (3) in the form

$$\lambda_{red.}\cdot \nu_{red} = \lambda_{oy}\cdot \nu_{oy} = \lambda_g\cdot \nu_g = \lambda_{bc}\cdot \nu_{bc} = \lambda_v\cdot\nu_v = C = \text{const.} \quad (4)$$

In the relations (3) and (4), $\lambda_{red.}$, $\lambda_{oy.}$, $\lambda_{g.}$, $\lambda_{bc.}$, $\lambda_{v.}$ are wavelengths of the "red", "orange-yellow", "green", "blue-cyan", "violet" photons; ν_{red}, $\nu_{oy.}$, $\nu_{g.}$, $\nu_{bc.}$, $\nu_{v.}$ are the frequencies of these photons; T_{red}, $T_{oy.}$, $T_{g.}$, $T_{bc.}$, $T_{v.}$ are periods corresponding to the wavelengths, respectively.
As follows from (4), the speed of a single photon is a function of two physical quantities characterizing the corpuscular-wave nature of this object of matter - the wavelength λ nd the repetition rate (frequency) of the photon-particle ν, the product of which is a constant value. At the same time, the contributions of each of these quantities to the numerical value of the speed of single photons C of various components of the light spectrum are different within the limits determined by relation (4). Thus, an increase in the photon wavelength λ by some percentage leads to a decrease in their repetition rate ν by the same percentage, and vice versa, an increase in the photon repetition rate ν some percentage leads to a decrease in their wavelength λ by the same percentage (see Figure and Table 1).
In this regard, it is obvious that the physical quantity C can be represented as
$C = V_{single\ ph.}(\lambda) + V_{single\ ph.}(\nu)$, conventionally calling $V_{single\ ph.}(\lambda)$ and $V_{single\ ph.}(\nu)$, respectively, the speed of single photons due to the wavelength, and the speed of single photons due to the frequency of their repetition.

Table 1 [6]

Spectral region visible light	Wavelength (nm)	Wave frequency (10^{14} Hz)
Red rays	760 - 640	3.95 ÷ 4.69
Orange and yellow rays	640 - 560	4.69 ÷ 5.36
Green rays	560 – 495	5.36 ÷ 6.06
Blue and Cyan rays	495 - 440	6.06 ÷ 6.82
Violet rays	440 – 400	6.82 ÷ 7.50

As seen from Table 1, the frequencies of "orange-yellow" photons exceed the frequencies of "red" photons from 1.187 to 1.357 times, "green" photons – from 1.357 to 1.534 times, and "blue-cyan" photons - from 1.534 to 1.727 once. When comparing "violet" and "red" photons, this difference factor reaches 1.9 times. There is also a frequency difference between the individual components of the "red", "orange-yellow", "green", "blue-cyan", and "violet" photons.
Naturally, the question arises: why is it necessary to state these facts known in advance? The answer is: it is important from the viewpoint of determining the propagation speed at the level of photons. The fact is that the devices used to receive light (photodetectors, photomultipliers) that come from a light source in devices for measuring the speed of light – discussed in the introduction of this article – as well as human eyes, react to the action of a complete wavelength of photons. In other words, they react to the frequency of single photons. This implies that these receiving devices capture only the frequency component of the speed of light $V_{single\ ph.}(\nu)$, which has varying values for different components of the light spectrum, as shown in Table 1.
To illustrate this, consider the following example depicted in Figure 1. For the sake of clarity, the process of "red" and "violet" photons passing through a recording device for receiving photons is shown. This device is perpendicular to the direction of photon propagation in measuring devices for the speed of light.

As observed in Figure 1, when a “red” photon with a wavelength λ_{red} and period T_{red} – i.e., frequency ν_{red} – passes through, nearly two “violet” photons with a wavelength $\lambda_{viol.}$ and period $T_{viol.}$ – i.e., frequency $\nu_{viol.}$ – also traverse the recording device of the measuring apparatus for the speed of light. In simpler words, the “frequency component” of the speed of propagation of individual “violet” photons, $V_{single\ ph.}(\nu_{viol.})$ is up to 1.9 times higher than the “frequency component” of the speed of individual “red” photons,$V_{single\ ph.}(\nu_{red})$.
Similar considerations apply to the “frequency components” of the speed of single photons at other wavelengths within the visible light spectrum. Thus, the difference in numerical values of $V_{single\ ph.}(\nu)$ for “orange-yellow”, “green”, and “cyan-blue” photons compared to $V_{single\ ph.}(\nu_{red})$ for “red” photons ranges from 1.187 to 1.357, from 1.357 to 1.534, and from 1.534 to 1.727, respectively.
The values of $V_{single\ ph.}(\nu)$ differ not only between the individual components of the light spectrum but also within each component.

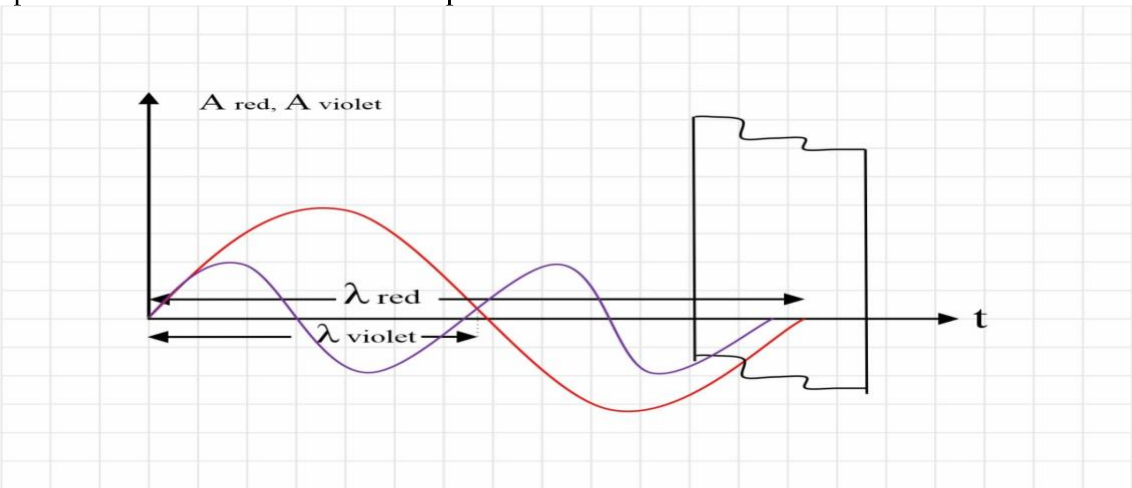

Figure 1. The depiction of the process in which “red” and “violet” photons with frequencies ν_{red} and ν_{viol} pass through a plane perpendicular to the direction of their propagation.

Let us now examine this matter from a different perspective, which also validates the aforementioned reasoning about the “frequency component” of the speed of individual photons. We define this component as a value equal to the number of photons N that pass through a plane perpendicular to the direction of light propagation—the front surface of the photodetector or photomultiplier used as recording devices for detecting light in instruments designed to measure the speed of light – per unit time t:

$V_{single\ ph.}(\nu). = N/t$

(5)

Let’s illustrate this using the example of the light wavelengths λ_{red} and λ_{viol} within the visible spectrum.

Let’s hypothetically consider a distance of one (1) meter in space through which light travels. Within this space, over the course of one second, according to the relation
$N_. = L/\lambda.$

(6)

We have
$N_{red} = 1m/\lambda_{red} = 1m/760nm = 10^9$ nm / 760 nm = $1.316 \cdot 10^6$ “red” single photons and
$N_{viol.} = 1m / \lambda_{viol.} = 1m/400$ nm = 10^9 nm/400 nm = $2,5 \cdot 10^6$ “violet” single photons passing through.

Considering that light propagates over a distance of $3 \cdot 10^8$ m/s, we can arrive at the frequency values presented in Table 1.
As evident, the number of single "violet" and "red" photons passing through a plane perpendicular to the direction of light propagation per unit time – essentially their repetition frequency – differs by a factor

$$m = V_{single\ ph.}(\nu_{viol.}) / V_{single\ ph.}(\nu_{red.}) = 1.9 \text{ times} \quad (7)$$

Specifically, the "frequency component" of the speed of more energetic "violet" photons with energy $h\nu_{viol.}$ is 1.9 times greater than the corresponding velocity component of "red" photons with energy $h\nu_{red}$ (since $\nu_{viol.} > \nu_{red}$).
This difference in the "frequency components" of the speeds of individual photons is particularly pronounced for wavelengths outside the visible spectrum, where the longest wavelength in the infrared range is $\lambda_{max\ ir.}$ = 1600 nm, and the shortest wavelength in the ultraviolet range is $\lambda_{min\ uv.}$ = 5 nm [7].
For the largest and smallest wavelengths of the infrared range, this difference factor is 1600 nm / 760 nm = 2.105, and for the largest and smallest wavelengths of the ultraviolet range - 400 nm / 5 nm = 80. And for the full spectrum of light, the difference factor between the "frequency components" of the speeds of unit photons reaches a value of 1600 nm / 5 nm = 320.
Naturally, in connection with this, the question arises: What speed was measured by Fizeau, Foucault, and their followers, particularly Michelson, whose data on this parameter of light are accepted and widely used to date? To answer this question, let us trace the formation of white light on the screen (in the photon-receiving device) of the measuring device for the speed of light. First, faster "violet" photons arrive at the screen surface, then "cyan-blue", "green", "orange-yellow", and finally, "red" photons arrive in turn, with the lowest frequency. This implies that the aforementioned classical scientists measured the speed of white light, the value of which corresponds to the sum of the "wavelength component" and "frequency component" of the speed of "red" photons in the visible region of the light spectrum. This sum equals the smallest value of the "frequency component" of the speed of light in this region.
Meanwhile, as deduced from the above analysis, the measured speed of light at the level of single photons, not only in matter but also in vacuum and in air (with a refractive index close to unity and equal to 1.00029), is determined by the repetition rate of these particles. Photons with a higher repetition rate propagate at a greater speed than photons with a lower repetition rate. Considering $E = h\nu$, this implies that more energetic photons propagate at a higher speed than less energetic photons, which is quite logical.
It's worth noting that the above considerations about the speed of light align with the findings of the work by Fobs and Young [3], particularly in the realm of the visible light spectrum. As early as 1881, they reported noticing different speeds with different colors, a detail that was disregarded both at that time and now by researchers.
Thus, the speeds of single photons for all wavelengths of the light spectrum are equal to each other and represent a universal constant (see relation (4)). Simultaneously, the "frequency components" of the speeds of single photons of various wavelengths, as recorded by the receiving device of measuring devices, differ.

The apparent paradoxical nature of such a statement at first glance can be explained as follows: as already noted at the beginning of the article, the speed of light is a function of two multiplicatively related physical quantities - the wavelength of light λ and its repetition rate ν. In this regard, an increase in the repetition rate of a single photon by a certain percentage leads to a decrease in the wavelength of this particle by the same percentage, and

conversely, a decrease in the repetition rate of photons leads to an increase in their wavelength by the same factor. Therefore, the validity of relation (4) is preserved.
Now, let us briefly delve into some considerations about the speed of light in substances based on a new approach to this issue at the level of single photons, specifically about the statement that the speed of light in matter depends on the frequency [8]. In reality, when light propagates through a substance, its wavelength and speed change, while the frequency remains unchanged:

$$\lambda_{.} = C/ n \quad \text{or} \quad V = (\lambda \cdot \nu) / n = (\lambda / n) \cdot \nu \qquad (8)$$

This is confirmed by the following example: when light, such as red light with a wavelength of 700 nm, transitions from vacuum into water with a refractive index of 1.331, it shifts to green light with a wavelength of 525.1 nm. However, a person underwater perceives not a green but a red beam, as human vision sensitivity is determined by the frequency of the light wave, not the wavelength. This demonstrates that the frequency of light, and therefore its energy E = hν, practically remains unchanged during such a transition [9], even though a portion of this energy is evidently absorbed within the medium (in water).
It should be noted that the above reasoning about the speed of light is valid not only for the spectrum of this object of matter but for the full spectrum of electromagnetic waves as a whole.
In this regard, the following question naturally arises: what is the connection between the above considerations and the results of the Vavilov-Cherenkov effect? The answer is this: the frequency of electromagnetic waves of gamma rays exceeds the frequency of ultraviolet photons by about four orders of magnitude, i.e., 10,000 times [10].

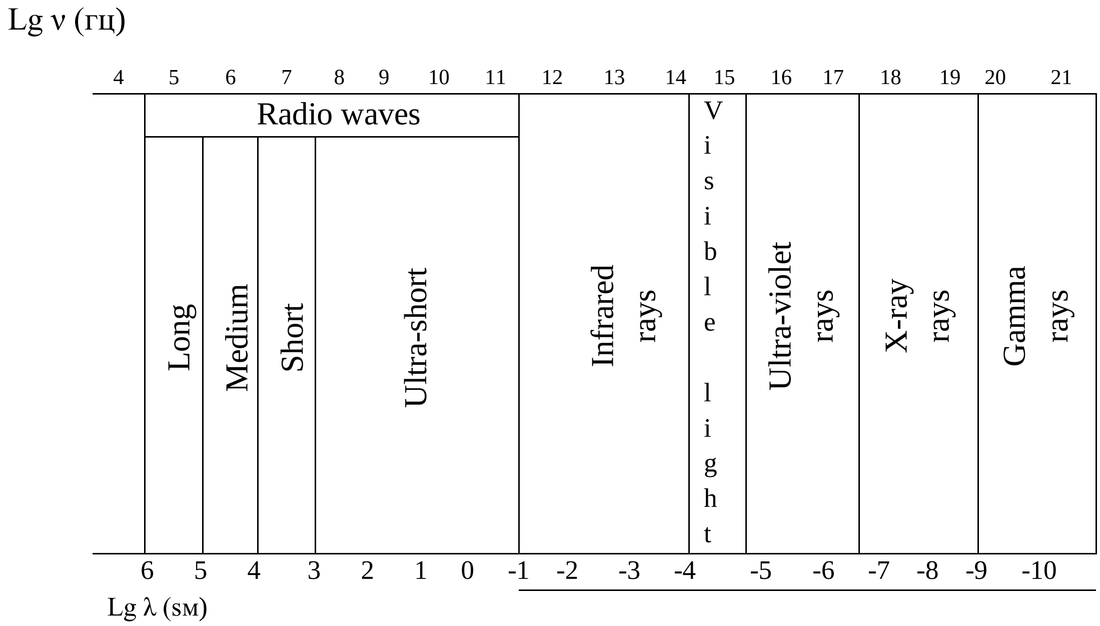

Figure 2. Full spectrum of electromagnetic waves [10]

This means that the value of the “length of the wave component” of the speed of these rays $V_{singly\ ph.}$ (λ) is negligible. When these rays propagate in a liquid, this value decreases by a factor of about 1.5 times.
At the same time, the value of the “frequency component” of this speed $V_{single\ ph.}(\nu_{gamma})$, as noted above, remains unchanged, and it is four orders of magnitude higher than $V_{single\ ph.}$ (ν_{bb}) and is close to the speed of light C, so that it is quite possible that the condition
$C/n < V_{single\ ph.}(\nu_{gamma}) < C$ holds for the electron inside the shell closest to the atomic nucleus.
Thus, the consideration put forward above about the speed of light makes it possible to explain (reveal) the reason for the fulfillment of this condition, on which the theory of I.E.

Tamm and I.M. Frank is based to explain this effect [11]**.

*** In 1958, the work of P.A. Cherenkov, I.E. Tamm, and I.M. Frank was awarded the Nobel Prize.*

Now let us briefly dwell on the possibilities of experimental implementation of the considerations put forward above about the speed of light, taking into account today's achievements. The following options are available here:

- To carry out the above classical experiments on measuring the speed of light (for example, Michelson's experiment) using existing quasi-coherent and quasimonochromatic laser facilities that generate light with different wavelengths as a light source.
- Implementation of classical methods for measuring the speed of light using selective optical filters in front of a recording device for the action of light - a photodetector, a photomultiplier for measuring the speed of light.
- Implementation of classical methods for measuring the speed of light using high-speed photodetectors sensitive to certain wavelengths, made of semiconductors and dielectrics with different band gaps, as a recording device for receiving light in devices for measuring the speed of light.

Conclusion

In the work based on the proposed new refined definition of a light beam in [1,2], which reveals the physical nature and properties of this object of matter at the level of photons, some considerations are put forward regarding the speed of light:

- A brief reference is given to research on measuring the speed of light - this most important parameter of light from a practical point of view, which has about three and a half centuries of history [3,4].
- The introduction of new concepts, such as the speed of single photons, the "length-wave component" of the speed of a single photon $V_{\text{single ph.}}$ (λ), the "frequency component" of the speed of a single photon $V_{\text{single ph.}}$ (ν).
- It is shown that although the propagation speed of single photons in vacuum of different wavelengths of the light spectrum is a function of two multiplicatively related physical quantities - the wavelength and frequency of photons, it remains a constant value [5]. However, the difference between the "wavelength and frequency components" of the speed of single photons within the light spectrum is noticeable, becoming significant in the ultraviolet range. Since the devices used to receive light (photodetectors, photomultipliers) coming from a light source, in devices for measuring the speed of light, as well as human eyes, react to the action of only a whole wavelength of photons, in other words, to the "frequency component" of the speed of single photons $V_{\text{single ph}}$ (ν), the readings of these devices, fixing the values of these speeds for different wavelengths of the light spectrum, are different. In the visible region of the light spectrum, this difference factor reaches up to 1.9; in the infrared range, it goes up to 2.1; in the ultraviolet region, it reaches up to 80; and in the full spectrum of light, it goes up to 320 [6,7]. However, the values of these speeds remain within $V_{\text{single ph.}}(\nu) < C$.
- It is noted that these results of the present work are consistent with the findings of Fobs and Young [3] in the visible region of light. They reported back in 1881 that they observed different speeds with different colors, a phenomenon that was ignored at that time and is still overlooked by researchers.
- An erroneous statement [8] that the speed of light in substances depends on its frequency is mentioned. In reality, in such cases, the wavelength of single photons changes, while their repetition frequency remains unchanged [9].

- Based on the above considerations about the speed of light, the reason for the fulfillment of the condition $C/n < V_{single\ ph.}(\nu) < C$ was revealed. This condition forms the basis of the theory of I.E. Tamm and I.M. Frank to explain the Vavilov-Cherenkov effect [10,11].
- Various methods for the experimental implementation of the above considerations regarding the speed of light are proposed. These methods take into account today's achievements in the development of quasicoherent and quasimonochromatic laser setups that generate light with different wavelengths, as well as the utilization of selective optical filters and high-speed photodetectors sensitive to specific wavelengths in devices for measuring the speed of light.
- It is noted that the considerations presented above not only apply to the speed of light but also extend to the speed of other components of electromagnetic waves.
- The results of this work seem to contribute to new applications related to the utilization of the speed of light.

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