Optik - International Journal for Light and Electron Optics 267 (2022) 169722

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Mach-Zehnder-based measurement of light emitting diodes temporal coherence

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A R T I C L E I N F O

Keywords:
Optical coherence
Light emitting diodes
Interferometry

A B S T R A C T

Objectives: The main objective of this work is to validate a Mach-Zehnder based interferometric method to measure the temporal coherence length of broadband finite size light sources such as Light Emitting Diodes (LEDs), and give a qualitative value of the temporal coherence length of white LEDs, for which nor their spectral width neither their emission peak wavelength are clearly defined.

Motivation: Low-coherence light sources such as LEDs have opened many possibilities in applications in which using lasers introduces coherent noise (speckle) that hinders the performance of interferometric measurement techniques. The coherence length is an important characteristic of light sources for scientific applications related to diffraction, holography, tomography, or interferometry. The spatial coherence of a source depends on the distance from the source to the observation plane and its size, while the temporal coherence is related to the emission spectral width and the emission peak wavelength. Therefore, the temporal coherence is a characteristic of each source.

Methodology and results: In this work, we use a Mach-Zehnder interferometer for the first time to measure the coherence degree and the temporal coherence length of quasi-monochromatic LEDs. We validate the technique by comparing the results to those obtained directly from the spectrum. Then, we use the tested interferometric method to measure the temporal coherence length of a white LED, for which neither the width of the spectrum nor the emission peak wavelength, are clearly defined. In this case, the Wiener-Khinchin theorem is used to validate the interferometric technique. A very interesting property of the method is that the temporal coherence length is obtained from a single measurement, without needing to perform a scanning. This method can be used also for other non-coherent sources such as halogen lamps, pulsed lasers, and so on. The obtained results will improve the characterization of light sources and the applications dealing with physical optics and electromagnetic interference.

1. Introduction

Light Emitting Diodes (LEDs) have become an essential part of our life. Almost all electronic devices have one or several LEDs with different functionalities. They have innumerable applications [1–3]. They can be used as warning or alert signal, as light lamps, in

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https://doi.org/10.1016/j.ijleo.2022.169722
Received 26 April 2022; Received in revised form 23 June 2022; Accepted 21 July 2022
Available online 22 July 2022

clinical diagnosis devices, optical fiber communications, interferometry, etc. There are many reasons why LEDs are used in many different applications but we should mention their low power consumption, long useful life, miniaturization possibility, and low production costs, among others. In addition, LEDs with different wavelengths, from UV to IR, even with broadband spectrum, are possible, for high and low emitting power [1–3]. The standard optical characterization of LEDs consists of measuring the angular distribution of light and the spectrum [4]. However, the coherence length is a very relevant characteristic for some scientific and technological applications, [5–8].

Propagation and interference of partially coherent beams have been analyzed previously in the literature [6–10]. The spatial coherence length of a light source measures the maximum distance between two points which emit at the same time and whose wavefronts remain with constant relative phase. On the other hand, the temporal coherence length of a light source measures the distance between two wavefronts emitted with a certain delay to each other from the same point that remain with constant relative phase between them. Recently, there has been an increasing interest about measuring the spatial and temporal coherence lengths of semiconductor-based light sources such as LEDs [11–16,18,19]. Usually, the temporal coherence length of light sources is measured by using a Michelson interferometer [14–16] or the double slit experiment [13,16–19], where the interference pattern at the output of the system is related with the coherence degree of the source, γ. In this work, we use for the first time a Mach-Zehnder interferometer, Fig. 1, to experimentally measure the temporal coherence of so-called non-coherent sources, such as LEDs. Different configurations of Mach-Zehnder interferometer have been used to measure the coherence degree of light sources such as lasers, [20–22], but we apply it to non-coherent sources for the first time. The Mach Zehnder interferometer offers more robustness and portability than other kinds of interferometers. Besides, the separation of the two beams can be made as large as desired, the test section is traversed only once, and white-light fringes can be obtained and localized in the same plane as the test section [23].

2. Experimental approach

In this section, the preparation of the experimental set-up and the experiments performed to check the functionality of the interferometer are explained.

2.1. Adjustment of the interferometer and used algorithm

As a first step, we start by aligning and adjusting the interferometer using an expanded and collimated long-coherence laser ($\lambda = 532.4\ nm$), model OXX-532–300-COL-PP by Oxxius, until no interference fringes are observed at the sensor plane. This can be done by tilting both mirrors in two perpendicular directions. In addition, one of them can be displaced parallel to one of the arms of the interferometer, as usual. Thus, we assure that both arms of the interferometer have approximately the same optical path from the source to the sensor. Now, by tilting horizontally one of the mirrors (x-z plane in Fig. 1), fringes parallel to the y-axis are obtained. We show in Fig. 2a an example of the interference pattern obtained with the mentioned laser. A camera, model HT-12000-S-M by Emergent Vision Technologies, whose pixel size and resolution are 3.45 μmx 3.45 μm and 4096 × 3000 pixels, respectively, is used to record the interferograms. We show in Fig. 2b the central area of the Fourier Transform of Fig. 2a, revealing the periodicity of the signal and the existence of background in the image.

The period of the fringes depends on the relative angle between both beams at the sensor plane. On the other hand, the visibility [7] depends on the optical path difference of both beams from the source to the sensor. To extract the coherence degree information, we use the Fourier Transform (FT) method firstly introduced by Takeda et al. [24]. The application of this method to our purpose requires the frequency analysis of the interferogram, ξ, at the sensor plane, which is given by

$$\xi = |b_1|^2 + |b_2|^2 + \gamma\left(b_1 b_2^* + b_1^* b_2\right) \tag{1}$$

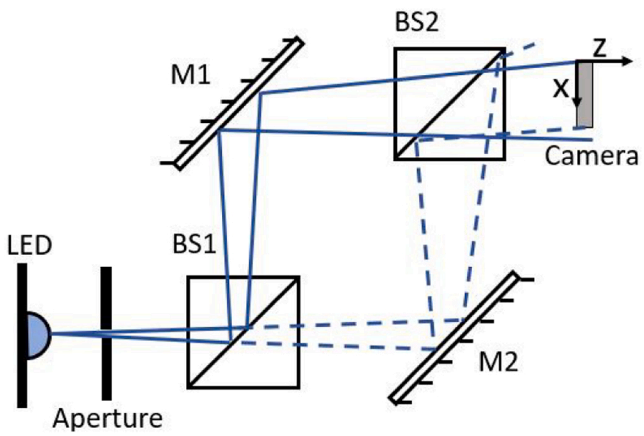

Fig. 1. Scheme of the Mach-Zehnder interferometer used to measure the coherence degree of the LEDs. M are mirrors and BS are beam-splitters.

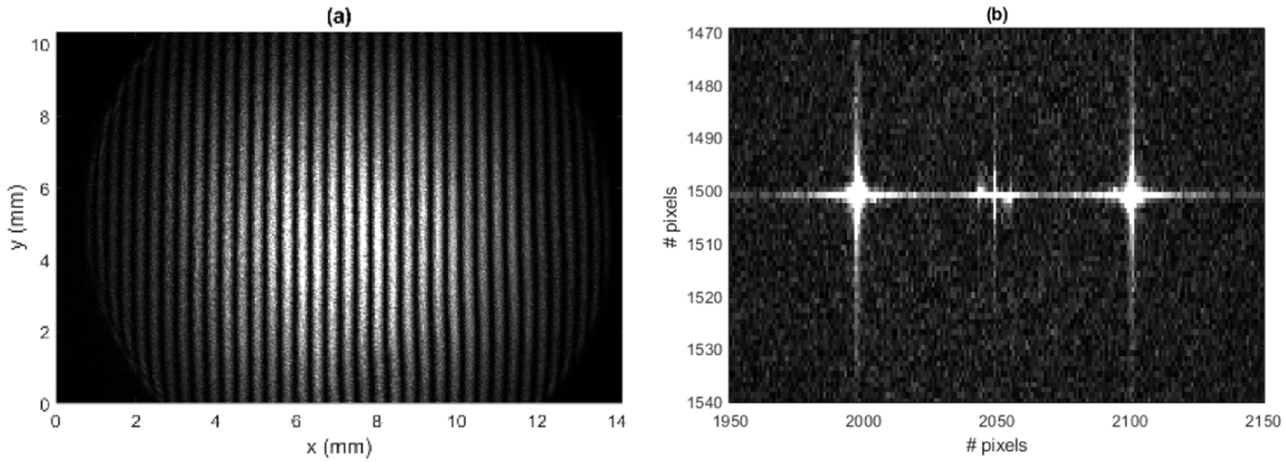

Fig. 2. (a) Example of the interference fringes obtained with the laser, (b) central area of the 2D Fourier Transform where the 1 % of the brightest pixels have been saturated.

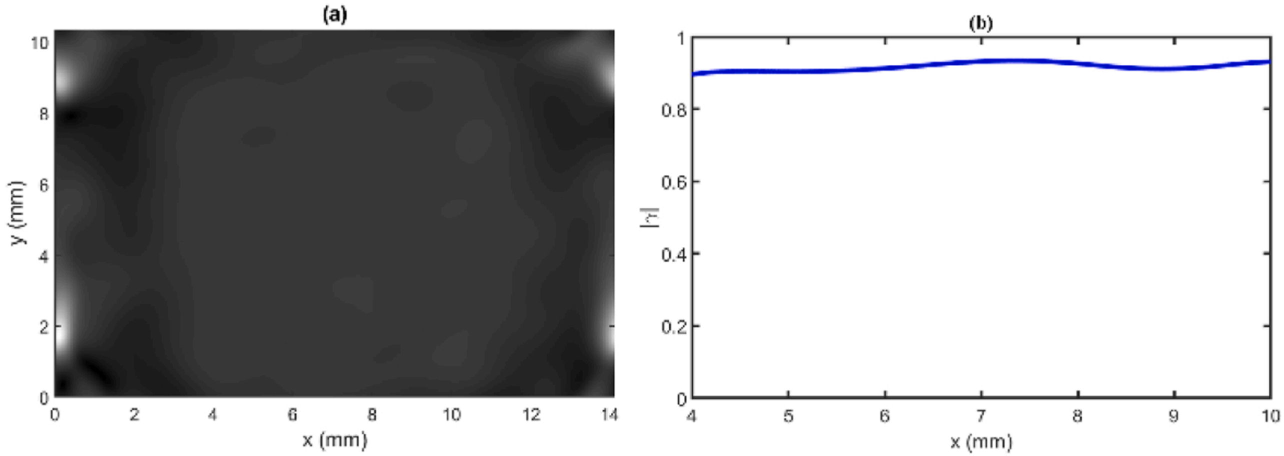

Fig. 3. (a) 2D coherence degree of the laser, (b) vertical integration of the central region of (a).

where b_n $(n = 1, 2)$ represent the field propagated through both arms of the interferometer and γ represents the coherence degree. Assuming that $|b_1| = |b_2| = b$, the FT of the interferogram results

$$\mathfrak{F}(\xi) = 2\ \mathfrak{F}(b^2) + \ \mathfrak{F}(\gamma b^2)[\delta(f - f_0) - \delta(f + f_0)] \tag{2}$$

where f is the spatial frequency and f_0 is the carrier frequency, from which the spatial period of the fringes, d, can be determined. On the other hand, from the FT of the interferogram, we can isolate the terms $a_0 = \mathfrak{F}(b^2)$ and $a_i = \mathfrak{F}(\gamma b^2)$, (Fig. 2b). Then, we can compute the inverse Fourier Transform to go back to the object space, and obtain the coherence degree as $\gamma = \mathfrak{F}^{-1}(a_i)/\mathfrak{F}^{-1}(a_0)$. For the long-coherence laser, the coherence degree is almost constant (Fig. 3) and equal to 0.9. Some deviation from the mean value can be observed at the edges of the 2D image, inherent to the filtering process. For this laser source we may assume that the temporal coherence is infinite and therefore, the coherence degree lower than one is due to the spatial coherence of the source, which cannot be considered as a point source.

Regarding the period of the interference fringes, it is related to the separation between diffraction orders at the frequency domain. Therefore, it affects to the first order isolation easiness. For shorter periods, the interference term results easier to isolate. In addition, the size of the window used to isolate it must be adjusted to cover the whole interference information. The shape depends on the distribution of the fringes and can be taken square, circular, and so on. In our case, we have chosen to use a circular one.

2.2. Obtention of the coherence degree of the so-called monochromatic LEDs

Now, with the interferometer adjusted, we replace the laser by one of the LEDs. The used LEDs are models THEM-CLBX (λ_0 =465 nm), THEM-CLAX (λ_0 =590 nm), and THEM-CLRX (λ_0 =625 nm), by Multicomp Pro, with λ_0 the emitting peak wavelengths. Once the LED and the other elements are placed into position, one must adjust very carefully the mirrors, angularly and longitudinally, to be able to observe fringes at the sensor plane. Notice that the output of all of them is highly unpolarized and the source cannot be considered as a point source. In fact, we show in Fig. 4 an image of two of the used LEDs (emitting area). As can be observed, they have a complex structure with electric connections and square shape.

As a consequence, the size of the source reduces the spatial coherence length. To minimize this effect, we couple a lens to the LED which produces a beam with 15° divergence, and place a small aperture (see Fig. 1) of around 1 mm diameter at 2 cm after the lens. We have checked that using the lens together with the small aperture improves the visibility of the interference fringes, since they increment the spatial coherence degree of the beam and improves the temporal coherence measurement. We show in Fig. 5a two examples of the coherence degree for two apertures of 1 mm and 12 mm diameter, respectively. They are obtained by performing the vertical average of the 2D coherence degree, similar to that shown in Fig. 3b, but for the blue LED. In addition, Fig. 5b shows the maximum coherence degree in terms of the distance of the camera plane, being z = 0 mm the closest position in which the highest contrast of the fringes has been obtained. It can be observed that the coherence degree decays more rapidly when a big aperture, or no aperture, is used in the set-up.

An example of interference pattern obtained with the blue LED is shown in Fig. 6a. It can be observed now the reduction of the visibility towards the edge of the image. It can be also appreciated that the fringes are smoother due to the lack of speckle, in comparison to Fig. 2a. Once the aperture is adjusted to the minimum possible, we obtain the coherence degree (Fig. 6b) by using the Takeda method, [24]. For completeness, Fig. 7 shows the vertical average of the coherence degree for the three quasi-monochromatic LEDs, and the smallest aperture (1 mm diameter).

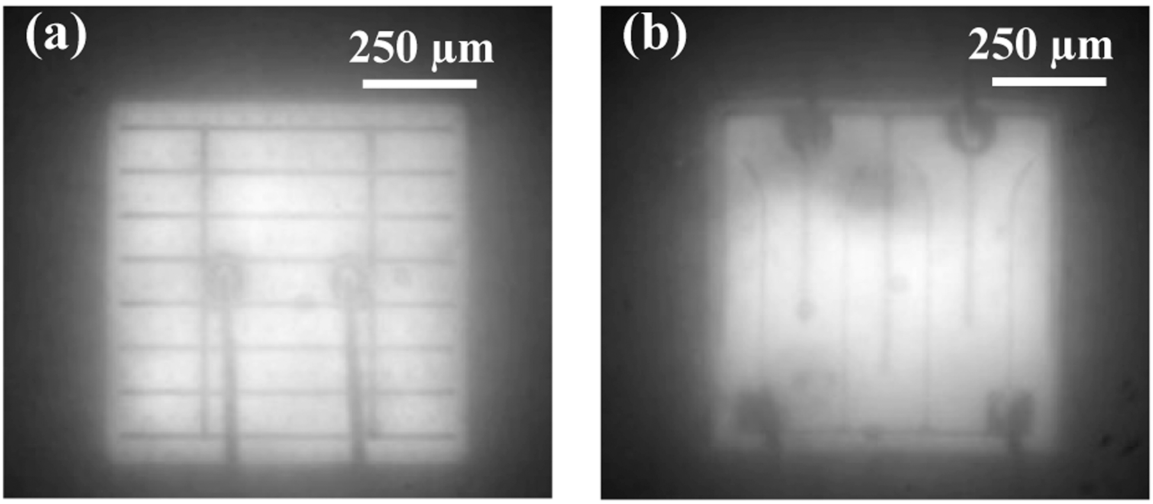

Fig. 4. (a) Amber LED (THEM-CLAX), (b) blue LED (THEM-CLBX). Both by Multicomp Pro. The red LED (THEM-CLRX) looks similar to the amber LED.

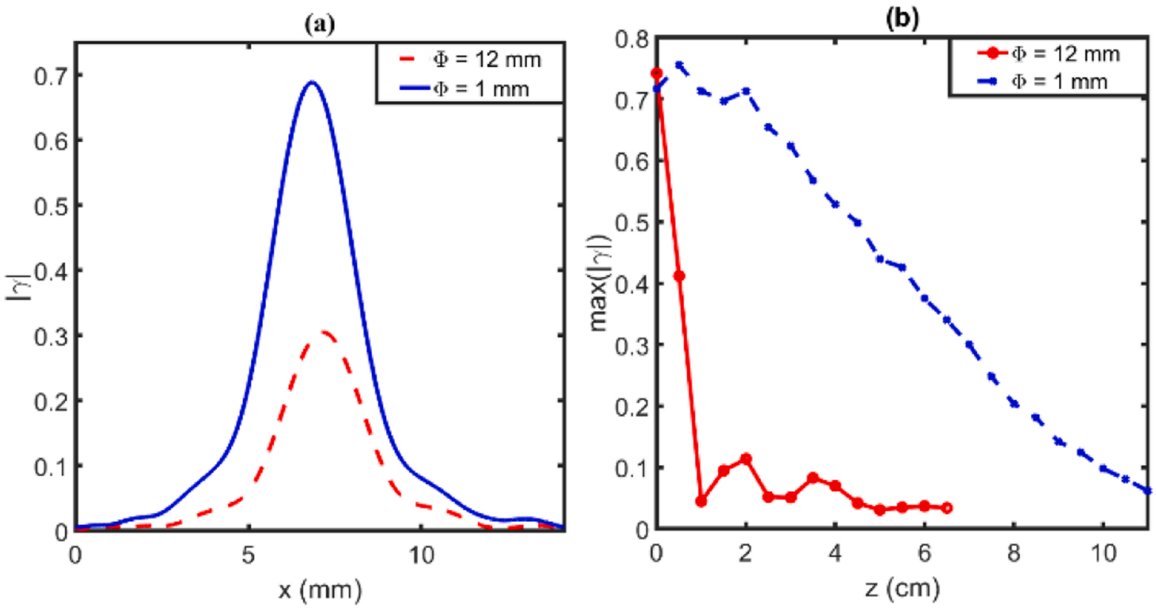

Fig. 5. (a) Example of coherence degree for both apertures with the same remaining parameters (z = 0.5 cm in b), (b) Effect of the aperture size on the maximum coherence degree for two sizes of aperture and the blue LED in terms of the distance between the camera and the initial position of the sensor (highest visibility of the fringes).

The transversal length, l, in which interference is observed can be estimated as the Full Width at Half Maximum of the spectrum (FWHM), l, of the Gaussian function fitted to the vertical average of the coherence degree. The period of the interference fringes at the camera sensor, d, is related to the central illumination wavelength, λ_0, and to the angle, θ (Fig. 8), between the two beams (B_1 and B_2) as

$$d = \frac{\lambda_0}{\sin(\theta)}. \tag{3}$$

On the other hand, the temporal coherence length, $L_{\text{interf.}}$, and the length, l, are also related to this angle, θ (Fig. 8), such that

$$L_{\text{interf.}} = l \sin\theta \tag{4}$$

Finally, from Eq. (3) and Eq. (4), the temporal coherence length is related to the measured l as

$$L_{\text{interf.}} = \lambda_0 \frac{l}{d} \tag{5}$$

Let us point out that, although a simple geometrical case has been chosen for Fig. 8, Eq. (5) is valid for any relative orientation between the laser beams and the sensor. All measured and calculated parameters are shown in the first three rows of Table 1.

As we have mentioned before, the temporal coherence of a light source is directly related to its spectral emission. Moreover, for quasi-monochromatic LEDs, such as those used in this work, it is related to the FWHM and the emission peak wavelength, λ_0. Thus, the values determined from the interferogram have been compared with the theoretical values obtained from the nominal spectrum of the LED sources. We show in Fig. 9 the three spectra of the used LEDs. The blue one has a wider spectrum and therefore, its temporal coherence length should be shorter. Considering that the spectrum of each LED fits a Gaussian function, the temporal coherence length may be obtained as [25].

$$L_{spect.} = \frac{4\ \ln(2)}{\pi} \frac{\lambda_0^2}{\Delta\lambda} \tag{6}$$

where $\Delta\lambda$ is the FWHM of the spectrum.

The results and calculated temporal coherence length for the three LEDs are also shown in the last three rows of Table 1. The theoretical coherence lengths, L_{spect}, result very similar to those obtained from the interferograms, L_{interf}. The discrepancies may be due to the difficulty of fitting the envelope of the interferometric term to a Gaussian function and obtain l, in particular, when the coherence degree does not decrease to zero within the area recorded by the camera (amber and red LEDs in Fig. 7).

2.3. *Obtention of the coherence degree of a white LED*

A more challenging problem is to determine the coherence degree and the temporal coherence length of non-monochromatic light sources. In this work, we use the tested interferometric method to obtain a quantitative value of the temporal coherence length of a

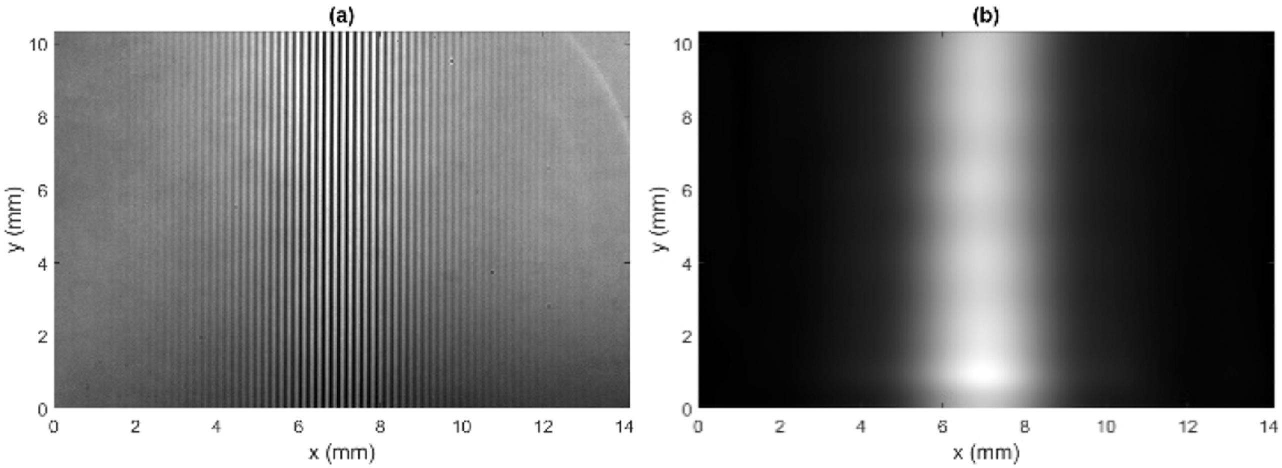

Fig. 6. (a) Example of interference pattern obtained for the blue LED, (b) 2D coherence degree.

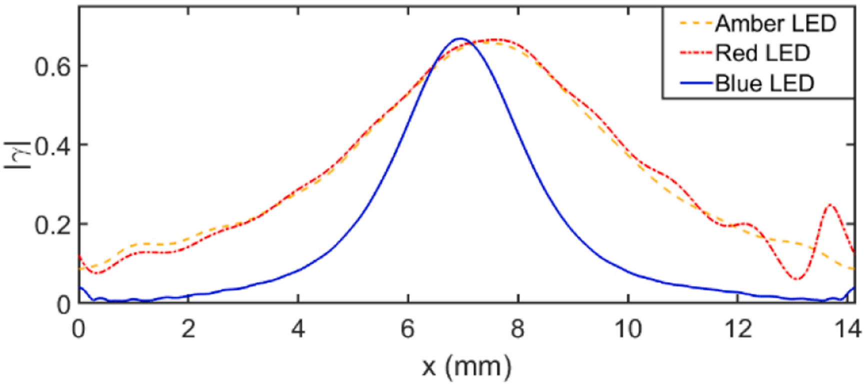

Fig. 7. Vertical average of the coherence degree corresponding to the three quasi-monochromatic LEDs by using the small aperture.

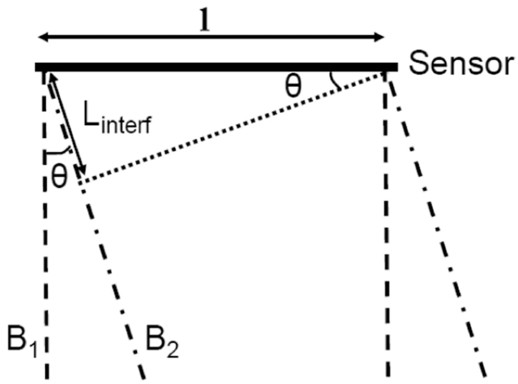

Fig. 8. Schematic explanation of Eq. (5) in which one of the beams reaches the sensor orthogonally, although, Eq. (5) is still valid for any angles of the beams, B_1 and B_2, at the sensor.

Table 1
Measured and calculated results for the temporal coherence length of the three quasi-monochromatic LEDs.

	Red LED	*Amber LED*	*Blue LED*
d (μm)	207.81	196.27	185.94
l (mm)	6.07	6.04	2.72
L_{interf} (μm)	**18.25**	**18.16**	**6.80**
λ_0 (nm)	625	590	465
$\Delta\lambda$ (nm)	15.05	15.48	27.5
$L_{spect.}$ (μm)	**20.52**	**19.29**	**6.94**

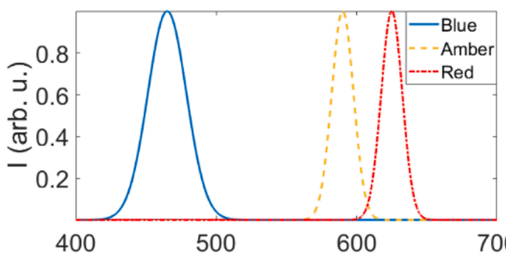

Fig. 9. Emission spectra of the three quasi-monochromatic LEDs.

white LED, model ASMT-Mx22-NNP00 by Avago Technologies. We show in Fig. 10 the emission spectrum of the white LED. As can be observed, it cannot be fitted to a Gaussian function and therefore, Eq. (6) is useless.

Some attempts to give a value of the temporal coherence length of white LEDs have been published previously [26], but with movable parts, which difficult the experimental performance. In this work, we just place the LED as the source of the interferometer and record the interferogram, Fig. 11a. Then, we perform the same process as for the so-called quasi-monochromatic LEDs and obtain the coherence degree, and its vertical average, Fig. 11b. As can be observed, the profile does not fit to a Gaussian function. It has a central narrow peak and some secondary ones around it with lesser height. On the other hand, the obtained coherence degree has the shape expected for sources with two partially overlapped emitting gaussian peaks like Fig. 10, [7]. Using the whole coherence degree profile and computing a Gaussian fitting as we have used for the quasi-monochromatic LEDs, the temporal coherence length calculated with Eq. (5) results $L_{White} = 4.9\ \mu m$, with $l = 1.25\ mm$, $d = 144.04\ \mu m$, and $\lambda_0 = 565\ nm$. It is smaller than those obtained for the three quasi-monochromatic LEDs, as it was expected. The temporal coherence length measured by this method is related to the whole length in which we may expect some amount of coherence and, therefore, interference. However, to ensure a good performance of some interferometric techniques, we might need to consider only the central peak. In that case, the temporal coherence length of the white LED results $L'_{White} = 1.84\ \mu m$. On the other hand, the Wiener-Khinchin theorem stablish that the Fourier transform of the source power spectrum coincides with the functional form of the temporal coherence degree, [27]. For the used LED, the expected temporal coherence length obtained from the spectrum of Fig. 10 results of $L'_{White}|_{W-K} = 1.69\ \mu m$, which is very similar to the experimental value.

3. Conclusions

Summarizing, in this work we have used and validated for the first time an interferometric method based on a Mach-Zehnder interferometer which is able to give a quantitative value of the coherence degree of so-called monochromatic Light Emitting Diodes and, therefore, the temporal coherence length. Besides, this method gives the value of the temporal coherence length from a single measurement without needing to perform a scanning. LEDs usually have a relatively big emitting area and therefore their spatial coherence is low. To increase it, we have placed a collimating lens and a small aperture after the LED, showing that smaller apertures increment the spatial coherence allowing to measure the interference fringes with more accuracy and in a more extended range of distances from the interferometer. The obtained results have been compared to those obtained directly from the emitting spectra showing high agreement. Then, we have used the tested method to obtain the coherence degree and the temporal coherence length of a white Light Emitting Diode whose spectral width and emission peak wavelength are not clearly defined. We have proved that the Mach-Zehnder interferometer-based method shown in this work is useful to measure the coherence degree and the temporal coherence length of white LEDs but it could be used for any other low-coherence light sources such as halogen lamps or pulsed lasers. From our point of view, the obtained results seem to be potentially useful for light sources characterization and also in applications dealing with electromagnetic interference and physical optics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

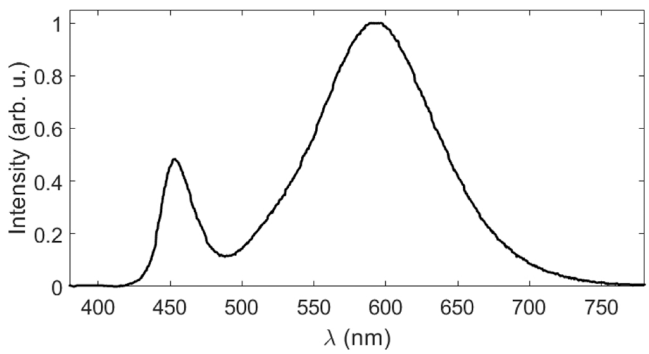

Fig. 10. Emission spectrum of the white LED, model ASMT-Mx22 by Avago Technologies.

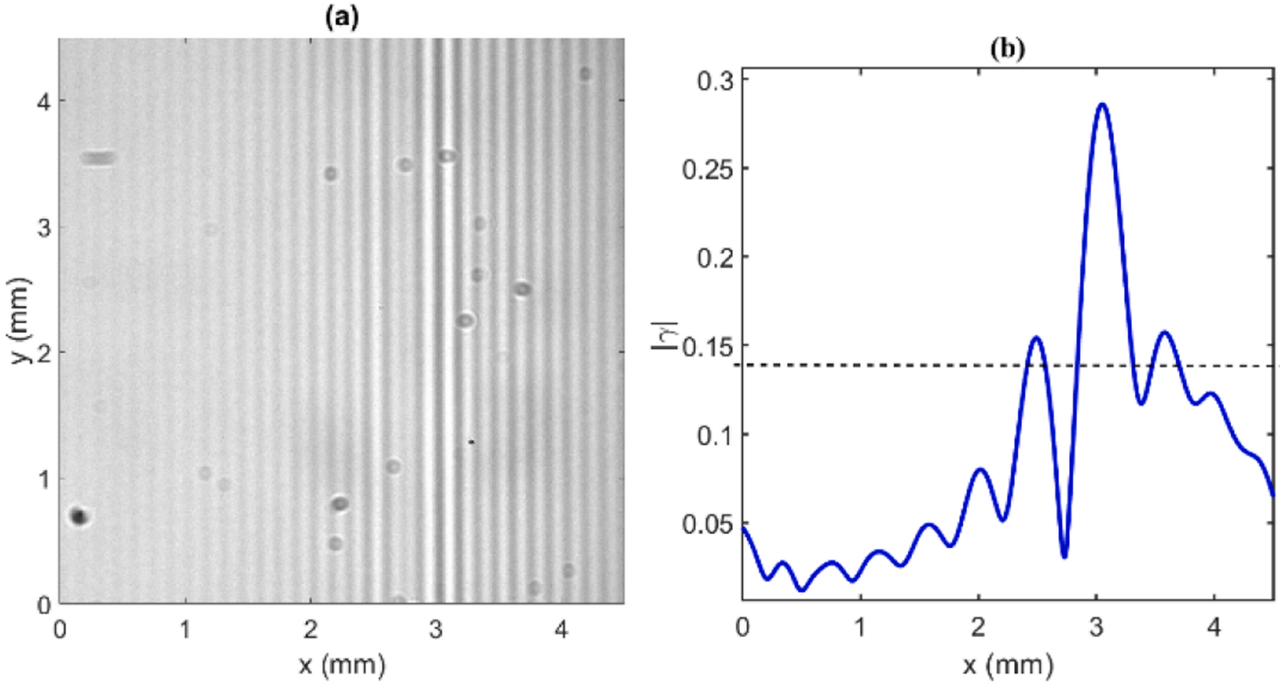

Fig. 11. (a) Interferogram recorded with the white LED at the same position as Fig. 6, (b) vertical average of the coherence degree. Dashed line denotes half the maximum of the coherence degree.

Acknowledgements

This work has been supported by Fundación Ibercaja and Universidad de Zaragoza (project JIUZ-2020-CIE-06), Gobierno de Aragón-Fondo Social Europeo (Grupo de Tecnologías Ópticas Láser E44_20), and Ministerio de Ciencia e Innovación of Spain (Project PID2020-113303GB-C22). Authors would like to acknowledge the use of Servicio General de Apoyo a la Investigación-SAI, Universidad de Zaragoza.

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