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Research Article

Implementation and Test of a LED-Based Lamp for a Lighthouse

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A novel sustainable source was developed for an existing Italian lighthouse, exploiting the light emitting diode (LED) technology and the norms evolution. The research work started with the optical design of the device, while this work concerns the realization, installation, and test of the new LED lamp. The lamp recombines multiple separated LEDs, realizing a quasipunctual localized source. After installation in the lighthouse, specific photometric tests verified that the proposed power-saving source satisfied the illumination requirements of the marine signaling norms. The advantages of the LED-based lamp are reduced energy consumption, enhanced efficiency, longer life, decreased faults, slower aging, and lower maintenance costs. The obtained LED signalling device is more durable and reliable. In the future the application of these power-saving long-life sources could be extended to other maritime signaling devices or to other traffic signs.

1. Introduction

During the last years, the illumination industry is experiencing an epochal transformation, basically due to the introduction of LED (light emitting diode) technology. This novel artificial luminous source is changing the scenario of lighting applications, thanks to the properties of the LED emission spectrum [1]. In many different applications [2–4], for indoor and outdoor lighting, LED-based lamps are gradually becoming the most efficient light source, substituting both incandescent and fluorescent lamps.

In general the purpose of sustainable sources is to fulfil the application requirements reducing consumptions and costs. Concerning the light sources, these are rapidly evolving towards very-high-efficiency and long-lifetime lamps, with a view to bring down the substitution operations for faults and aging. Currently, LED sources appear to be the most promising solution for energy saving and environmental sustainability; in fact, LED-based sources are more efficient than fluorescent lamps, discharge lamps, halogen tungsten lamps, and traditional incandescent lamps. The key characteristic of a LED is the form of its emission spectrum, which creates and maintains its efficiency. The advantages of LED lamps are reduced energy consumption, enhanced efficiency, longer life, decreased faults, slower aging, and lower maintenance costs.

Lamp replacement is an important intervention in the lighting sector, because of the need not only to save energy but also to limit light pollution and to reduce maintenance costs [3, 5–8]. In the perspective of sustainable progress, the research for more efficient lighting devices is stimulated also by political actions. In practice, laws and regulations are acknowledging the recent technical progress undergone in the lighting industry, adapting norms [9, 10] and standards to the new commercial products emerging on the market.

The area of applicability of the proposed LED-based device is maritime signaling; the light source was designed to be mounted into the lighthouse of Tino Island, located in the north-west of Italy. Optical project and mechanical design were developed to fulfil the strict requirements of the norms for marine signaling [9, 10] and to adapt the novel sustainable source to replace the old lighthouse lamp [11, 12]. The LED-based lamp was realised and appropriate photometric tests [13–15] verified that the required illumination levels were distributed in agreement with the pertinent norm. It was then mounted on the lighthouse of Tino Island and several field measurements certified the validity of this swap of the lighthouse lamp. The intent is to be able to substitute in an existing lighthouse the usual high-consuming short-life lamps with power-saving long-life LED-based sources [2, 5, 7]. This operation of lamp replacement is foreseen also for other lighthouse typologies and can be extended to other traffic signaling systems.

2. Photometric Tests

A prototype of the proposed LED lamp was realised on the basis of the optical project [11, 12], especially developed as luminous source of Tino Island lighthouse. The new lamp has a duration longer than an incandescent lamp and its power consumption is 135 W, versus some hundreds of Watts for a discharge lamp or 1000 W for a halogen lamp [13, 15]. The fail of one or few LEDs does not affect the operability of the lighthouse; it only appears as a gradual reduction of emitted light, while most of usual lamps would be switched off. This LED-based lamp is resistant to transportation and storage, and its installation in the lighthouse of Tino Island does not need mechanical changes in the existing lamp frame. The weaknesses with respect to traditional lamps are higher costs and slightly lower illumination level actually obtainable using commercial products.

Photometric measurements are of primary importance to comprehend if the novel source works correctly [16, 17] and if it complies with the maritime signaling norms [9, 10, 13]. Initially the functionality of the new LED source was tested in laboratory, referring to its optical design; successively specific field tests, executed on the LED-based lamp installed in the lighthouse, assessed its emission features on the field, in working condition.

The next sections describe optical tests and measurements performed on the LED device, which are listed below in order of execution:

(i) photometric measurements in laboratory,

(ii) measurement of the illumination produced on the inner surface of the Fresnel lens of the lighthouse, in relation to identical measurements performed with the traditional source (incandescent lamp),

(iii) assessment of the luminous range of the lighthouse through observations made from the sea,

(iv) measurement of temporal behaviour of the lighthouse flash.

3. Source Installation and Laboratory Tests

3.1. Mechanical Sizes and Distances. The working principle used to optically design the new LED-based source is that it recombines the light of a circular LED matrix to obtain a quasipunctual localized source. The rays coming from the LEDs, placed on a flat plate, are combined by a concave mirror near its focal point. A second mirror, with the shape of a cone, located near the first mirror focus, guides the rays in an annulus centered on the cone axis.

Lamp working principle and luminous rays' path are illustrated in Figure 1, where the flat plate mounting the LEDs matrix is shown at the bottom. A complete image of the new source is presented in Figures 2(a) and 2(b). The photometric centre of the optical system is considered at midheight of the cone (18.1 cm height from the LED plate). The emission angles are geometrically calculated with respect to the photometric centre (theoretical point inside the cone where the light reflected from the upper mirror would be focused), taking into account the dimensions of the structure. In fact, due to the LED plate and the upper mirror, which screen the emission, the maximum upper and lower angles (referring to the horizontal line) of aperture are, respectively, 15.8° and 49.4°. It must however be emphasized that, since the real photometric centre is not punctiform, the source can generate also rays outside of the geometric emission angles.

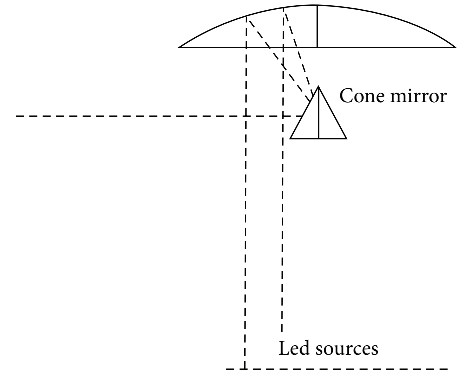

Figure 1: Working principle of the LED-based source.

3.2. Beam Width. In order to measure the effective vertical width of the beam that starts from the cone, appropriate measurements were performed by means of a diode laser and a screen. The experimental apparatus is described in Figure 3. A laser diode, with case size of a few centimetres, was positioned to emit a vertical beam. The laser was placed in correspondence with the plate mounting the LEDs matrix and it is moved along a radius of the plate. For each point of the radius (in steps of 1 cm), starting from the innermost one (at the base of the cone) up to the outer one, the position of the point where the laser beam encountered a screen placed at fixed distance was recorded. The radius, starting from the plate, is firstly reflected by the concave mirror, then from the cone, and then hits the screen.

The distance D between the screen and the centre of the cone is 182.7 cm.

From the obtained data the total angle of emission results to be 54.8 deg (18° above horizontal line, 36.8° below).

3.3. Luminous Intensity. The measurements of light intensity on the vertical plane were performed by measuring the *illuminance* produced by the source on a screen placed at 166.2 cm from the photometric centre of the lamp. The measurements were initially carried out with the source in normal operating conditions, with the cone obscured, in order to evaluate the light portion due to the reflection only on the concave mirror and the stray light in general, which does not contribute to the efficiency of the source.

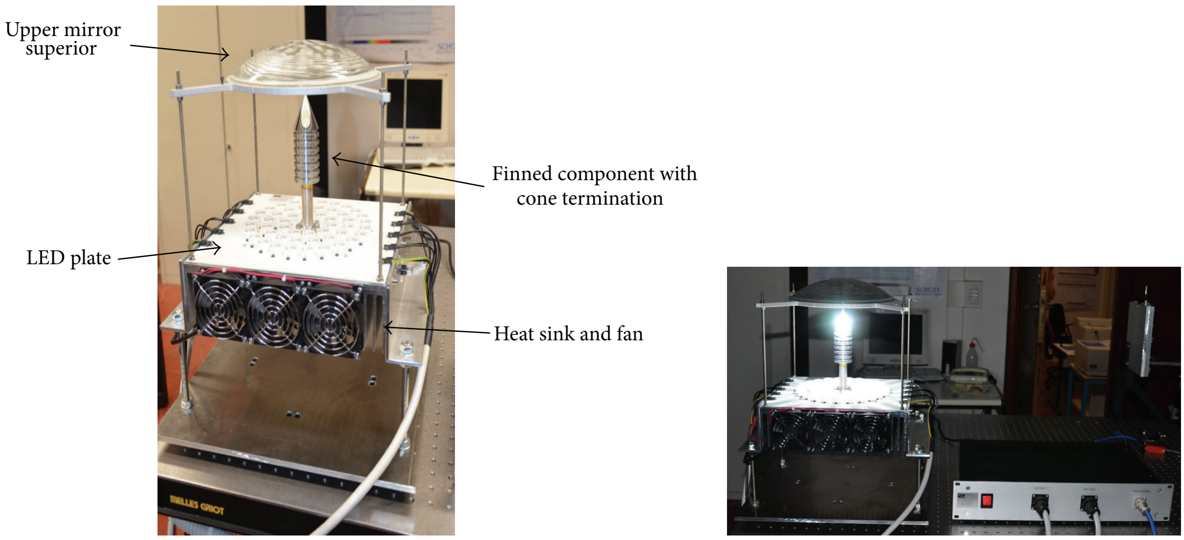

Figure 2: (a) Assembled LED-based lamp. (b) The LED lamp assembled and running.

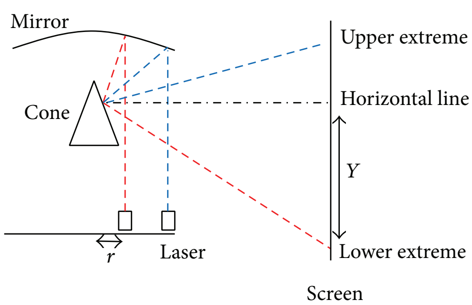

Figure 3: Experimental set-up to measure the angle of vertical emission.

The results are shown in Figure 4, as normalized light intensity, in arbitrary units. The solid line indicates the contribution due only to the cone, obtained for difference. The figure evidences the contribution due to the light coming directly from the concave mirror (stray light), especially below −30°.

The maximum value of the luminous intensity, corresponding to the horizontal direction, is 1000 ± 50 Cd.

From previous measurements, it is possible to evaluate, approximately, the difference between the new source and the former incandescent lamp. Indeed, the latter had a power of 1000 W, which means, considering luminous efficiency of 20 lm/W, a radiant flux of 20000 lm. This radiant flux value corresponds to a luminous intensity (equal in each direction) of about 1470 Cd, compared to an average value in the area of interest of the new source of about 1000 Cd that is 68% of the original luminous intensity. It is in a good agreement with the theoretical previsions.

4. On-Site Source Installation and Illuminance Tests

4.1. Mounting the Source inside the Lighthouse. The new LED source was assembled and installed in the lighthouse of Tino Island (La Spezia, Italy) at the end of August 2012. The first step was to replace the incandescent bulb with the realised LED-based lamp. The second step was to correctly place the LED source; it was achieved by aligning the centre of the source, the centre of the Fresnel lens, and the horizon [13, 14].

The picture in Figure 5 illustrates the source mounted on Tino Island's lighthouse.

4.2. Illuminance on the Inner Surface of the Fresnel Lens. Illuminance measurements were performed on the Fresnel lens with a portable light meter Minolta T10, in order to evidence differences of the LED lamp behaviour with respect to the incandescent source. In practice, the light emerging from the point source that impinges on the Fresnel lens, will be, after refraction, redirected toward the horizon outside the

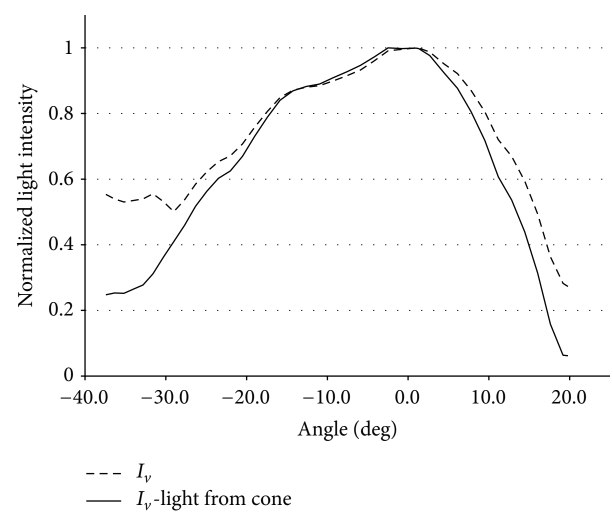

Figure 4: Normalized light intensity, in arbitrary units. Solid line: contribution only from the cone. It can be seen that beyond the range −29/18 deg the contribution is largely due to the light coming directly from the concave mirror (stray light).

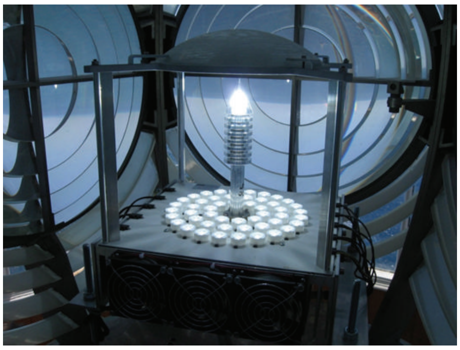

Figure 5: New source placed in the lighthouse, 3/4 view from above.

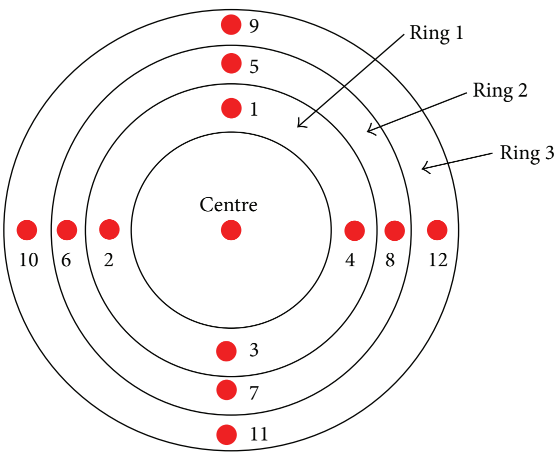

Figure 6: Measuring points on the inner surface of the Fresnel lens.

lighthouse. Due to the particularity of the application, the intensity measurements are not easy to perform, so this is a good evaluation of the differences between incandescent lamp and LED source. The measuring points are marked, each with its own number, in Figure 6, which depicts the central part of the Fresnel lens (inner surface), view from the inside of the lighthouse.

Figure 7 reports the difference, in percentage, between the illuminance obtained using LED lamp and incandescent lamp; points 1–4 are located in the inner ring; points 5–8 belong to the medium ring, while points 9–12 are sited on the external ring (see Figure 6). The variation of illuminance difference among the measurement points in the case of LED lamp and incandescent lamp depends on both the beam shape of the LED lamp, slightly downward-oriented due to the ray blocking of the top mirror (see Figure 3), and the dimming due to the top mirror supports. The highest percentage difference with respect to the case of incandescent source was in fact measured in points 1, 5, and 9 and points 7, 11: the first three points represent the upper part of the lens, less irradiated because of being near the maximum upper emission angle; analogously for points 7 and 11 in the lower part of the lens.

The new LED source illuminance on the inner surface of the Fresnel lens results, as average value, 68.8% of the illumination obtained with the incandescent lamp. This illuminance percentage is in excellent agreement with the

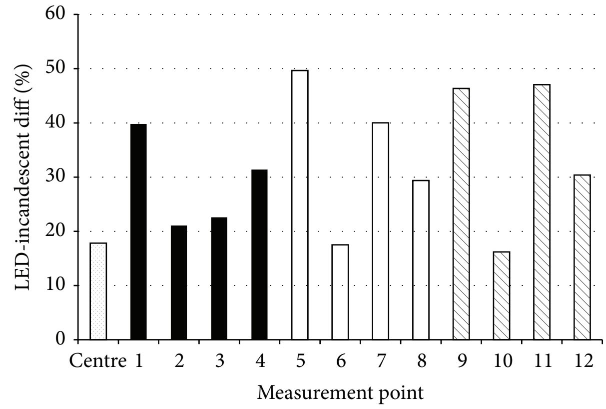

Figure 7: Percentage illuminance difference on the Fresnel lens between incandescent lamp and LED lamp.

evaluations performed starting from laboratory measurements (Sections 3.2-3.3). Hence a decrease of more than 30% on luminous intensity could be expected, as evidenced also in the simulations [11] executed to define the optical design of the LED-based lamp.

5. Measurements and Assessments at a Distance

5.1. Qualitative Analysis: Visual Evaluation from the Sea. In order to evaluate the range of the new beam of the lighthouse, in the night between April 17 and 18, 2013, exploiting a ship provided by the Italian Navy, visual assessments were performed from the sea.

The night was clear, moonless, and with good visibility (qualitative assessment). The deck of the ship was about 3 meters over the water's surface.

To give the maximum of objectivity to the visual assessment, this was performed simultaneously by five subjects and repeated, navigating the vessel at a distance between 20 and 30 nautical miles (1 nautical mile = 1852 meters) from the lighthouse on Tino Island.

Considering that the height of the light H above sea level is 117 m and that the observer is placed at a height h of about 4.7 m (= 3 m + 1.7 m), the geographical range D is estimated at 26.5 nautical miles through the following relation [18]:

$$D = 2.04\left(\sqrt{h} + \sqrt{H}\right). \quad (1)$$

In the worst case, the source was visible from all subjects up to a distance of 26.6 miles and at a distance of 27.4 nautical miles was no longer visible by any observer. In the best case, the source was visible from three subjects up to 28.5 miles. D values greater than the mentioned observations may depend on refractive phenomena in the atmosphere. Therefore the distance range is definitely greater than 26.5 nautical miles and it can reasonably be set equal to 27 nautical miles. An important observation is that all subjects indicated that the flashes were sharp and well distinguishable from the context.

Owing to vibrations caused by the engine and the roll/pitch of the vessel, it was not possible to perform measurements with the instrumentation described in the

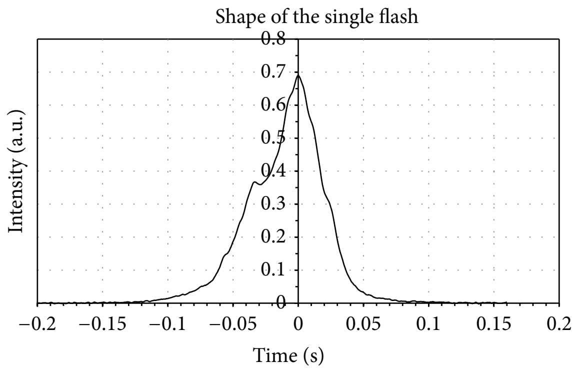

FIGURE 8: Average time trend ("form") of each flash intensity.

next section. For this reason some photometric measurements were executed from the ground with the purpose of quantifying the optical characteristics of the lighthouse emission.

5.2. Qualitative Analysis: Beam Width and Light Intensity Assessment from the Ground. In the night between 13 and 14 May, 2013, quantitative measurements of shape and duration of the flashes were carried out from the mainland. These measurements were performed from a height of about 50 m above sea level at a distance of 7.44 km from the lighthouse itself. Due to the angular aperture of the beam, it was fully visible even if the observation did not occur exactly at the same height of the lighthouse source (which is placed at 117 m above sea level).

The lighthouse was pointed through a telescope (Meade STX90, with pupil diameter D = 90 mm, focal length F = 1250 mm, f-number $f/13.8$). The telescope STX90 has two outputs: one (*output 1*) for an eyepiece for direct vision and one (*output 2*) for shooting photos or video; a folding mirror allows selecting the desired output. Thanks to a special adapter a photodiode was mounted on *output 2* and the photodiode output, properly preamplified, was displayed on an oscilloscope (TDS3032 Tektronic), which also had the ability to save the resulting track on the disc. Several temporal shapes of the flashes were recorded by means of this equipment.

Averaging the various recorded flash shapes, a fairly reliable shape of the mean flash, shown in Figure 8, was obtained.

It can, therefore, be evinced that the average FWHM duration of a single flash is 0.06 seconds. Given that the system of lenses of the lighthouse is moving at an angular velocity of 24 deg/s, it can easily be obtained that the beam width (FWHM) is 1.44 deg. This value is in good agreement with the estimation calculated during the design phase: about 1.4 deg of beam width.

In order to evaluate the intensity of the light emitted by the lighthouse from the seaside location Fiascherino, the sensor of the experimental apparatus was replaced with a fast calibrated flash luxmeter (LMT, mod. SF100).

Given the difference in altitude (above sea level) of the observation point with respect to the lighthouse (difference = 47 m), the measurement is not performed on the emission peak but at an angular distance of about 0.4 deg from the maximum. According to the emission profile resulting from the simulations, the measured values must be multiplied by a factor R equal to 1.259 to obtain the measurement on the maximum peak.

The maximum illuminance recorded by the sensor is equal to 0.4 lux, which, considering the conversion factor due to the entrance and exit pupil areas of the telescope and its transfer function, leads to an illuminance E_{ts} on the entrance pupil of the telescope equal to 0.00174 lux.

The formula to obtain the *candela* (Cd) value corresponding to an illuminance value at a distance of 7.46 km is [13]

$$I_{7.46\,\text{km}} = R \times E_{\text{ts}} \times 7460^2 = 122000\,\text{Cd}. \tag{2}$$

In order to be able to estimate the luminous intensity at the exit of the lens, it is essential to assess the averaged transparency of the atmosphere in the 7.46 examined kilometres at the time of measurement. This transparency is affected by the quantity of suspension in the atmosphere (fog, humidity, etc.).

In practice the output intensity I_0 from the lantern and the intensity $I_{7.46\,\text{km}}$ at 7.46 km of distance are related by the Lambert-Beer formula:

$$I_{7.46\,\text{km}} = I_0 e^{-\mu_e \cdot 7.46}, \tag{3}$$

where μ_e is the extinction coefficient in km^{-1}.

In order to determine the extinction coefficient, it is necessary to refer to the atmospheric condition during that night. In fact the data in "IALA Recommendation E-200-2 On Marine Signal Lights Part 2—Calculation, definition and notation of luminous range" [10] report the relation between extinction coefficient and moisture: extinction coefficients versus wavelength for the marine aerosol model for different relative humidity values and constant number density of particles. The data available for the day 13/05/2013, measured in the hinterland (Luni-Sarzana meas. station, historical meteorological database, http://www.ilmeteo.it/) are: average temperature 19°C, average visibility 10 km.

Reasonably, on the sea and at night, when the measurements were made, it can be supposed to have humidity over the maximum humidity recorded, since the data refer to the hinterland. Assuming a humidity value between 90 and 95% (on the coast, in Livorno, 65 km south, 94% humidity that night), at visible wavelengths, the extinction coefficient results are between 0.25 and 0.35, on average equal to 0.3. This leads to estimating the output luminous intensity from the lens as follows:

$$I_0 = \frac{I_{7.46\,\text{km}}}{e^{-\mu_e \cdot 7.46}} = \frac{122'000\,\text{Cd}}{e^{-0.3 \cdot 7.46}} = 1'144'000\,\text{Cd}. \tag{4}$$

This quantity must absolutely be considered a rough estimation since the atmospheric attenuation varies dramatically with the weather conditions at the time and therefore the value may vary greatly within the same night. However, the documentation IALA and in particular the "Recommendation E-200-2 ON Marine Signal Lights Part 2—Calculation, definition and notation of luminous range" [10] show that the luminous intensity for a distance range around 26 nautical miles is greater than 10^6 Cd, in agreement with the observations made from the ship (Section 5.1).

6. Conclusion

All surveys, visual and quantitative, confirm both the substantial agreement between implementation and project and the effectiveness of the new source as a possible substitute, in maritime lighthouses, of incandescent lamps. The new sustainable LED device offers significant advantages reducing energy consumption, improving reliability, and limiting maintenance costs. There is a little disadvantage consisting in a decrease in the luminous intensity of about 30%, which slightly changes the theoretical range of the LED-based lamp, although marine observations show no substantial modification of the luminous range with respect to the case of incandescent lamp.

The proposed system is also open to possible modifications that can further improve performance, particularly with regard to power-saving and reliability. A subsequent engineering work may also lead to greater compactness of the source (with performance advantages) and a decrease in costs. Finally, the availability of new LEDs with higher efficiencies and/or increasing luminous power could allow a further enhancement in performance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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