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Research Article

Design of Optical Collimator System for Vehicle Speed Gun using Non-Imaging Optics

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Abstract. Vehicle speed guns are usually used in normal sunlight conditions (daytime). If we want to use vehicle speed guns in low light conditions (nighttime), the illuminator is needed to provide sufficient light for the vehicle speed gun to take photos. The illuminator must fulfill two requirements: (i) using the infrared wavelength to ensure that the driver is not startled by dazzling eyes by the illuminator of the proposed speed gun system and (ii) high energy efficiency to make the illuminator compact leading to the use a small battery system to improve the portable of the proposed vehicle speed gun. In this study, an illuminator using a collimator system designed by using non-imaging optics is introduced. LEDs with infrared wavelength are chosen from the library of LightTools™, the structure of collimated is designed to transfer the illumination from the LEDs array to a square area of 3x3 m^2 to cover the vehicle to detect the vehicle number plate. The design process is built based on the conservation of optical path length in the Matlab program. After that, the designed collimator is simulated in LightTools™ software. The promising results of the simulation in LightTools™ show that the collimator can efficiently transfer light from the LED array to the target area with a uniformity of about 70 % and optical efficiency of about 80 %.

Keywords: Illumination, Collimator, Vehicles speed gun, LightTools, non-imaging optics, Matlab programming, Non-imaging optics.

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1. Introduction

A vehicle speed gun operates based on the principle of the Doppler effect; thus, it can work in any light condition (Hamelmann *et al* 2019). However, a vehicle speed gun must be used with a camera to take photos serving as evidence. Therefore, a vehicle speed gun is usually used in the daytime. If it is used at night, a flashlight is required for the camera. The flashlight for the speed gun must use infrared illumination with wavelengths longer than 750 nm to guarantee the safe movement of drivers. In addition, a flashlight should have high power to enable the camera to take photos from a long distance, around 70 m to 100 m. This requirement leads to the need of using a large battery for the flashlight. A battery system that is not compact will hinder the applicability of the speed gun system as a portable mobility device. On the other hand, a small battery with high mobility does not have enough energy for a high-power illumination instrument of a speed gun.

There is an effective solution for this problem which is to use LED (light-emitting diode) because of its great light intensity with small energy consumption. As a result, a compact battery system working for a long time is available, thus improving the mobility and performance of vehicle speed guns. LEDs typically emit light with a beam view angle of about 120-degree angle if no optical lens or reflector is used (Liu *et al* 2019). Therefore, a LED array for illumination is just effective only if it is designed and used with accordant optical lenses with special application. In this case, if optical lenses are not suitable for LEDs array, light from LEDs will not spread and distribute into the target area, meaning a waste of energy.

To design a collimator for a LED array, non-imaging optics (Winston *et al* 2005, Chaves *et al* 2008) is a suitable method compared to imaging optics thanks to its simplicity and flexibility. Non-imaging optics are completely suitable for applications such as illumination (Koshel *et al* 2012) and aiming for transferring radiation energy (O'Gallagher *et al* 2008) to the target area. Especially, non-imaging is usually used for designs that need a high tolerance to ignore the effects of error in the assembly and production processes of optical elements (Winston *et al* 2018). Non-imaging optics was first invented by Winston *et al* (2005) and then developed by Minano *et al* (2015), and Benitez (2004) for many applications in illumination and solar energy (Dross *et al* 2004, Gutierrez *et al* 1996, Chong *et al* 2009). In non-imaging optics, there are two main methods for optical design such as flow line, and simultaneously multiple surfaces (SMS) (Chaves *et al* 2008, Benitez *et al* 2004). The flow line is typically used to design compound parabolic concentrators (CPCs) while the SMS method, which is modern

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and flexible, has many applications in designing optical lenses in 2D and 3D such as concentrators, distributors, collimators for Concentrator photovoltaic systems, daylighting, and illumination systems (Buljan *et al* 2014, Gul *et al* 2016, Martin *et al* 2002, Tsangrassoulis *et al* 2008). In the SMS method, a lens is built consisting of two surfaces, which are determined by positioning all points over these surfaces. Each point is determined by using the conservation of optical path length. Non-imaging optics is used widely in recent years in the design of optical concentrators such as studies by Pham *et al.* (2018), Pham *et al* (2019), Mohedano *et al.* (Mohedano 2016), and Ryu *et al.* (2006), etc. In addition, contributors and distributors in daylighting systems are designed by using non-imaging optics in published papers by Pham *et al.* (2017), Irfan *et al.* (2014, Irfan *et al.* (2012), etc. These aspects show that non-imaging optics is a suitable method to design an optical system for a vehicle speed gun.

Furthermore, focusing on the improvement of the performance of the vehicle speed gun, there are some studies on the design of light sources for replacing ultrasound signals such as a study from Erik Kreifeldt *et al.* (1996), a study from Kumar *et al.* (2019, Kumar *et al* (2014), and a study from Muzal *et al.* (2016). In those studies, the authors have tried to use laser sources to detect the velocity of the vehicle. Although the speed of light is higher than sound in the Doppler effect, however, the accuracy is still limited and that makes the controller more complicated. On the other hand, some studies focus on the design of a control system to improve the performance of vehicle speed guns by handling the reflected signal. There are some studies in this field such as studies from Adnan *et al.* (2013), Mandava *et al.* (2018), and Nguyen *et al.* (2014). All these mentioned analyses illustrate that many methods can be used to improve the performance of the vehicle speed gun depending on the specific condition of the application. However, almost vehicle speed gun systems in commercial can work well in daytime conditions. Therefore, in this work, we limit the project to applying the vehicle speed gun in the nighttime condition to detect the speed of cars without modifying much of the main system. The extended application for the nighttime condition is used by adding the illuminator which can use efficient energy in a compact battery. In the field of estimating the speed of cars in nighttime condition, there is few studies come from Setiyono *et al.* (2021), Hassan *et al.* (2016), Dharhir *et al.* (2019), and Abdel-wahed *et al.* (2022), etc. Although there are few studies on the estimation of speed guns at nighttime, however, almost focus on data analysis and image processing to detect the speed of the vehicle. There is no literature for design a collimator for the illuminator of the vehicle speed gun. Thus, the design of a collimator of illuminator with high energy efficiency is promising to apply the normal vehicle speed gun in nighttime conditions without increasing cost much in real conditions.

In this paper, the study focuses on the design of an optical collimator system for a LED array with infrared wavelength (from 750 nm to 850 nm) applied to a vehicle speed gun system. The collimator is designed using non-imaging optics based on the conservation of optical wavelength to guide the light emitting from the LED array to a target 3x3 m^2 with a distance of about 100 m. The structure of each collimator is divided into two parts for the construction of each: one part uses total internal reflection while the other part uses the refraction phenomenon to design a Cartesian oval surface to collimate the light from LED. Each collimator is simulated in Matlab, then the data is imported to LightTools^{TM} to do simulation and ray-tracing to evaluate the performance of the collimator.

2. Design of the collimator for vehicle speed gun

2.1 Design of collimator using refraction for each lens

To design a collimator for LED, the dimension of LED is needed. LED is chosen from the library of LightTools^{TM} with specifications as shown in Fig. 1. From the dimension of each LED, a LED array consisting of 8x8 LEDs is proposed with dimensions of 180x180 mm with 64 high-power infrared LEDs.

The collimator is an array consisting of 64 single lenses in which each lens acts the role of a collimator for each LED. All lenses are combined by positioning on the transparent substrate. The lens is constructed by two surfaces: the entry surface is flat while the exit surface is a cartesian oval surface. The light emitting from LED is refracted at the entry surface, then the refracted light will be refracted again at the exit surface to be a parallel ray outside of the lens to reach the target area with a distance of about 100 m. In actual conditions, LED is not a point light source. However, for the sake of design simplicity, LED is assumed as a point light source. The position of the point light source is determined as the intersection of two edge rays of the light emitted from LED with a 120^0 angle as shown in Fig. 2.

Based on the position of the focal point, the shape of the collimator is designed which is shown in Fig. 3. In this design, the conservation of optical path length is the most important. The edge rays emitting from unreal focal point F with angle 120^0 are determined. In addition, the entry flat surface of the collimated lens is placed in front of the LED. From this information, the position of the edge ray going into the lens is determined. The ray entering the lens will be refracted at the entry surface following Snell's theorem:

$$\sin\alpha = n \times \sin\beta \tag{1}$$

Where α and β are incident and refracted angles compared to the normal of the entry surface while n is the refractive index of Poly Methyl Methacrylate (PMMA) for the wavelength of 750 nm.

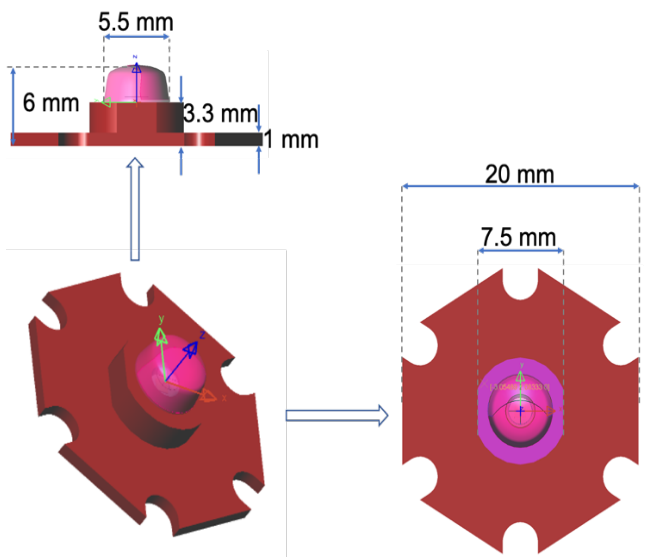

Fig. 1 The shape and dimension of LED that is chosen from the library of LightTools^{TM}

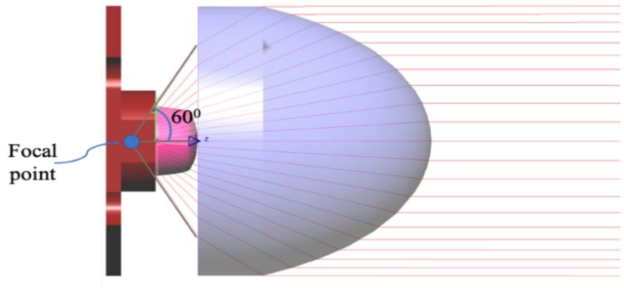

Fig. 2 The position of the unreal focal point as a point source

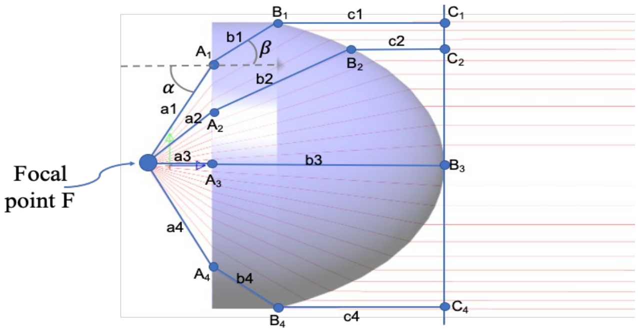

Fig. 3 The point light source from Focal point *F* illuminates the lens in the flat entry surface and the bundle ray exiting the lens is an array of parallel rays

By using Snell's theorem, the direction of refracted ray can be determined. Depending on the thickness of the lens's base, the position of point B_1 is calculated. The refracted lights are guided by the Cartesian oval surface to exit the lens as parallel rays. The Cartesian oval surface is evaluated by using the conservation of optical path length leading to every point of exit surface is determined as shown in Fig. 3.

$$a1+n\times b1+c1=a2+n\times b2+c2=a3+n\times b3=a4+n\times b4+c4=\cdots=OPL \quad (2)$$

Where *a1, a2, a3, a4, b1, b2, b3, b4, c1, c2, c4* are partial optical path lengths of the rays emitting from LED; *OPL* is the sum of optical path lengths of each ray. All of them are length with the unit in mm.

In this design, A_1, A_2, A_3, and A_4 are the positions of the light entering the lens in the entry surface where Snell's law is used to determine the directions of refracted rays. B_1, B_2, B_3, and B_4 are points to evaluate the Cartesian Oval surface. C_1, C_2, B_3, and C_4 are points that are in the same wavefront. The conservation is always right for one wavefront.

In conclusion, the position of focal point *F* for the point source is firstly assumed to evaluate the pan of light coming to the entry surface. Snell's law is secondarily used to determine the directions of any refracted light. The thickness substrate's lens and directions are used to estimate the two extreme points of the Cartesian oval surface. Finally, the conservation of optical path length and numerical method is used to determine representing points of the Cartesian oval surface. Combining every point calculated to estimate the Cartesian oval surface (freeform exit surface). As a result, the collimator is designed completely consisting of a flat entry surface and the freeform exit surface to collimate the light emitting from LED to go to the target area. After that, the data can be used to revolve around the center axis to create a 3D collimator in LightTools as shown in Fig. 4.

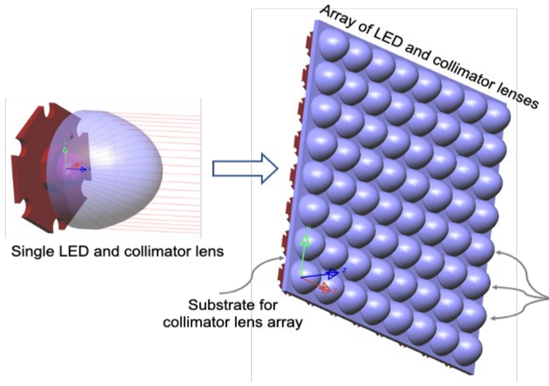

Fig. 4 The single LED and collimator and array of LEDs and collimators

To apply this design of LED and collimator lenses to vehicle speed guns, the lenses are combined by using only one substrate for all lenses. Each lens will receive a light emitting from LED to transfer the light to exit the lens as a bundle of parallel rays. However, a drawback of this design is that it is highly sensitive to alignment. If the array of collimators is not assembled accurately, all lenses will have errors in making parallel rays leading to the bundle of rays, thus cannot transfer correctly to the target. Therefore, this design requires a high-accuracy assembly process, which is hard to achieve in practical conditions. To overcome this drawback, another design of collimator is proposed in which the collimator lens is designed by using simultaneously total internal reflection and refraction. The design of this collimator lens is introduced in detail in the next part.

2.2 Design of collimator using total internal reflection and refraction in each lens

In general, the collimator lens can be divided into two parts: the first part is designed using refraction while the second part is designed using the total internal reflection. Dimensions of the first part and second part can be chosen depending on the size of the LED's lens. The collimator lens has a structure with a hole in the center to hold the LED, the exit surface is flat as shown in Fig. 5.

In this design, the LED collimator lens comprises a refractive center section (front center entry), a refractive center section (side center entry), and a side reflective surface where the reflection is due to total internal reflection (TIR). The sections of the front center entry and side center entry capture a different angular portion of the light source as shown in Fig. 6.

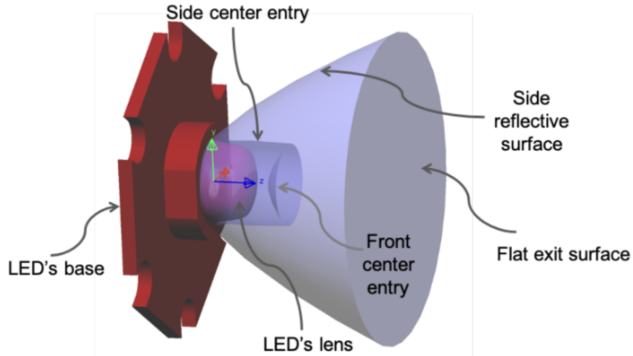

Fig. 5 LED with collimator lens with a hole in the center to hold LED's lens

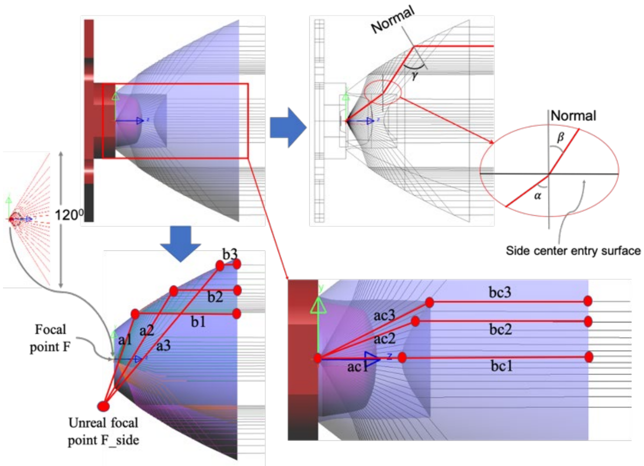

Fig. 6 The collimator lens with two portions for LED using TIR and refraction to design

There are some requirements for this design which are (i) the hole center diameter is bigger than that of the LED's lens; (ii) the inner height of the hole center is higher than that of the LED's lens; (iii) diameter of exit surface is equal to the outer circle of LED's base. Fig. 5 shows the components of the LED and collimator lens.

The process for the design of the LED collimator is described in several steps as follows.

Step 1. The designer chooses the total height of the collimator lens and the angular portion of light spread for the front center entry and side center entry.

Step 2. Using the diameter of the center hole, the surface where a portion of the bundle of rays comes into the lens is estimated. The side center entry surface can be freeform or cylindrical. However, to make the design simple, the cylindrical surface is chosen to receive a portion of illumination emitting from LED.

Step 3. The bundle of rays coming to the side center entry is refracted at the interface to go to the side reflective surface following Snell's law. The shape of the side reflective surface is estimated so that the rays are reflected as a total internal reflection. To calculate the side reflective surface, the position of unreal focal point *F_side* is chosen and the conservation of optical path length is used in Eq. 3.

$$n \times a1 + n \times b1 = n \times a2 + n \times b2 = n \times a3 + n \times b3 = OPL \quad (3)$$

Where n is the refractive index of the lens medium for the light with a wavelength of 750 nm. The side reflective surface adapts Eq. 3 should be a portion of the parabolic surface with the focal point being unreal focal point *F_side* in Fig. 6.

In this step, the incident angle γ of a ray in Fig. 6 should be greater than the critical angle $\gamma_{critical}$ which is used to calculate the total internal reflection in Eq. 4.

$$\mathrm{n} \times \sin \gamma_{\text{critical}} = n_{air} \times \sin 90^0 \quad (4)$$

Where n_{air} is the refractive index of air.

If the incident angle γ is smaller the $\gamma_{critical}$ incident light will refract at the side reflective surface to go outside of the lens. When the incident angle γ increases, the refractive angle will increase immediately until reach a value 90^0 at which the total internal reflection happens leading to the refracted beam will be changed to the reflected beam inside of the lens. Therefore, if the value of n of the lens is 1.486 and the value of n_{air} is 1, the critical angle $\gamma_{critical}$ should be about 42.4^0.

So that if that requirement for incident angle γ is not adapted, the position of unreal focal point *F_side* should be chosen again until the requirement adapting.

Step 4. Based on the inner height and diameter of the center hole, the positions of *AC1* and *AC3* are estimated completely. The conservation of optical path length is calculated for every ray coming to the front center entry in Eq. 5.

$$a1 + n \times b1 = a2 + n \times b2 = a3 + n \times b3 = OPL \quad (5)$$

Any ray coming to the front center entry adapts the conservation of optical path length leading to the freeform of the front center entry surface is estimated.

Step 5. When the side center entry and the front center entry are estimated already, the data of the crossectional view revolves around the center axis along the LED collimator to get a collimator lens as Fig. 5. After that, an array of LEDs and collimators can be created to be a flashlight for a vehicle speed gun as shown in Fig. 7.

In this structure of collimator lens, the requirement for the high accuracy assembly process is reduced significantly because every LED and collimator is independent of others. All these steps to design the collimator lens are carried out in the Matlab program. The data of the cross-sectional view of the collimator is calculated using a numerical method. After that, the discrete data from Matlab is inserted into LightTools™ software to draw the collimator in 3D (3 Dimensions). The flowchart of the design procedure is shown in Fig. 8. In general, the design is firstly carried out in Matlab based on some initial parameters relating to the characteristics of LED. In programming, the conditions to stop the process are always important. In this process, stopping conditions are total internal reflection and size of the collimator lens. TIR has to happen at the side reflective surface while the size of the collimator lens should be equal to the size of the outer circle of the LED's base. If the designed lens is not meet these requirements, the unreal focal point *F_side* should be chosen again to obtain all requirements. The data collected in Matlab is just a 2D design. After that, the 2D data from Matlab is inserted into LightTools to draw the object in 3D by revolving the shape of the lens in 2D. The 3D lens draw in LightTools™ is used to simulate for estimation of the performance of the proposed system.

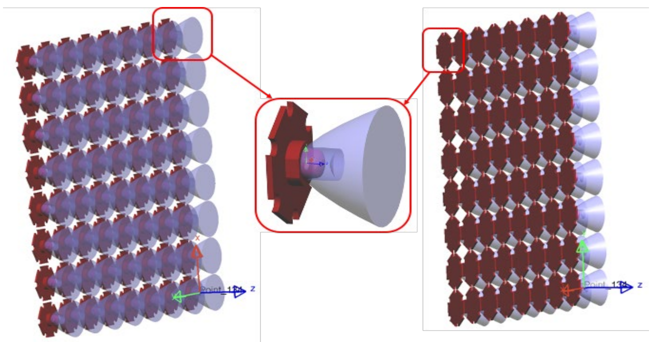

Fig. 7 The array of LEDs and collimator lenses applied to the vehicle speed gun

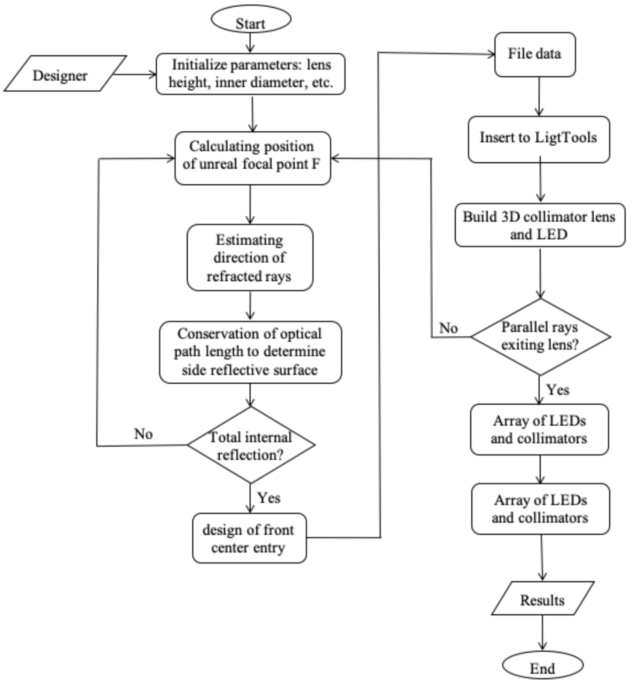

Fig. 8 The flow chart to design the array of LEDs and collimators applied to a vehicle speed gun

In addition, the uniformity of light distribution over the target is also an important parameter to estimate the performance of the proposed system which is estimated in LightTools™ and is calculated in Eq. 6.

$$U = 100 - \frac{max - min}{average} \times 100\% \tag{6}$$

where *average*, *min*, and *m*ax are the mean value, lowest value, and highest value of the intensity of light over the target area, respectively.

3. Results and Discussion

This study aims to apply the designed collimator lens to a flashlight system for a vehicle speed gun performing in the night condition with a compact and effective battery. The main requirement of the illuminator of the proposed vehicle speed gun is the wavelength belonging to the range of the invisible spectrum for safe driving. It depends on the properties of the Charge Coupled Device (CCD) camera used for the vehicle speed gun system. Generally, the illuminator should have a wavelength in a range from 750 nm to 950 nm. For convenience, in this study, the characteristics of LED with a wavelength of 750 nm are chosen from the LightTools™ library as shown in Fig. 1. PMMA material is a good selection for collimator lenses because of its high transmission coefficient of about 93 % (Ali 2015) as shown in Fig. 9.

In this study, the design of the collimator lens is applied to the vehicle speed gun system so that the collimator lens will have a small spread angular distribution of exiting light to distribute the light to the target area. That small spread angle will be obtained by modifying the side reflective surface or modifying the flat exit surface be a curve surface. The modification of the side reflective surface is chosen to make the design process simple. The spread angle is calculated depending on the distance from the light source to the target area. There are two ways to illuminate the vehicle a long distance of around 100 m or a shorter distance of about 30 m.

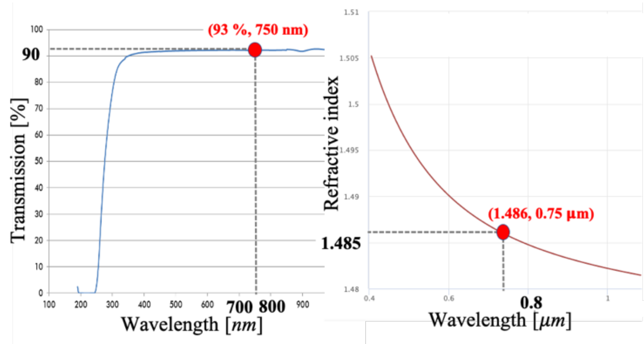

Fig. 9 The refractive index and transmission of PMMA material following the wavelength for the designed collimator lens

If the light source is placed at the same place as speed gun systems, the distance from the light source is long so that the spreading angle should be small even equal to zero. For long distances, a random defect of emission light from LED is enough for the spread of light at the target area and it is difficult to reach the requirement of lux on the target area in outside illumination for a CCD (Charge Coupled Device) camera taking photos (Vu 2017). Therefore, the flashlight source can be remotely controlled by using wireless communication to put the light source near the target area. Wireless communication is a mature technology and it can be applied easily to the vehicle speed gun system. The distance from the light source to the target area (car's position) is chosen at about 30 m as shown in Fig. 10. Table 1 illustrates the parameters of simulation and ray-tracing of the optical system in LightTools™ software to estimate the performance of the designed collimator lenses in the flashlight source for the vehicle speed gun system.

The discrete data from Matlab is inserted into LightTools™ to build the flashlight source. Fig. 11 a) shows the ray-tracing of a single LED and single collimator. The results show that the rays emitting from LED are divided into two sections. The outer section entering the collimator is refracted to go to the side surface where the rays are total internal reflected to exit at the collimator lens at a flat exit surface. The center section of bundle rays enters the collimator at the freeform surface where the directions of rays are changed to go to the exit surface as parallel rays. However, LED is not a point source in reality and simulation leading to the lightly spread of the bundle of rays exiting the collimator. The ray-tracing is carried out for an array of LEDs and collimators which is illustrated in Fig. 11 b).

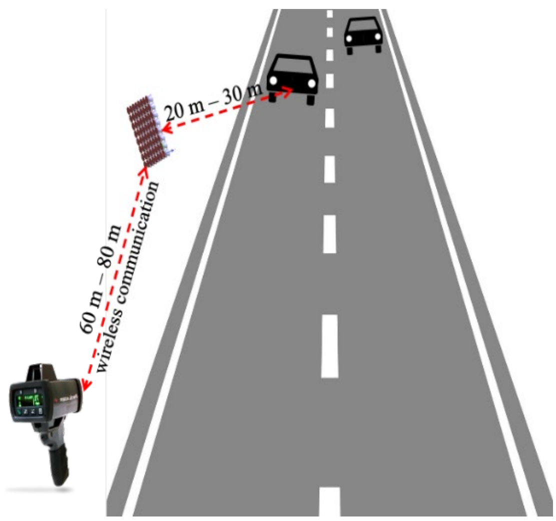

Fig. 10 The way to set up the flashlight source for a vehicle speed gun using wireless communication to reduce the distance from the light source to the target vehicle

Table 1
Parameters for simulation and ray-tracing in LightTools™

Items	Value
Wavelength	750 nm
The outer circle of the LED's base	21.5 mm
Distance from the light source to the target area	30 m
Spreading angle	< 2.9^0
Inner center heigh	6.5 mm
Diamter of inner center hole	6.0 mm
Total height of collimator lens	15 mm
Diameter of the flat exit surface	21.5 mm
Lens material	PMMA
Refractive index of PMMA	1.486
Number of rays for simulation and ray-tracing	3.000.000 rays
Power of single LED	1 W
Number of lm per Wat	500 lm
Number of lenses and LEDs	8 x 8 = 64 elements
The dimension of the flashlight source consists of 64 elements	180 x 180 mm^2
Target area	3 x 3 m^2
The average luminance on target are	150 lx

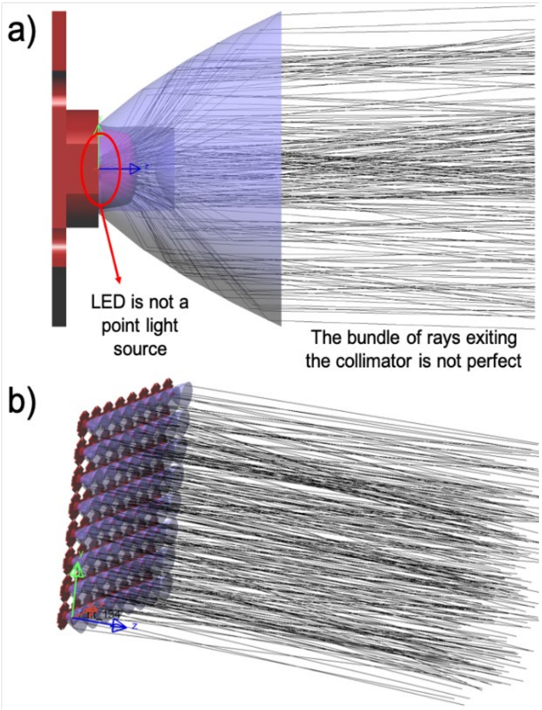

Fig. 11 The ray-tracing of a) a single LED and collimator and b) an array of LEDs and collimators

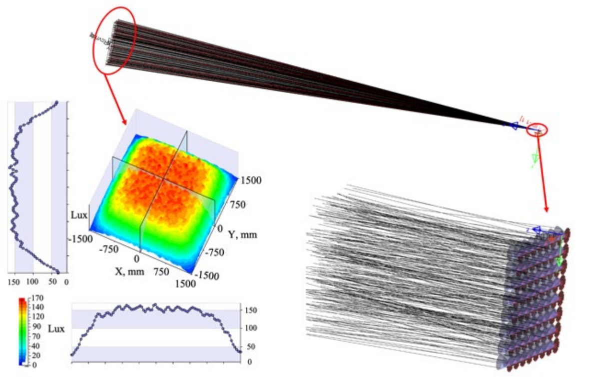

Fig. 12 Ray-tracing of the flashlight source in LightTools™ and illumination distribution over the target area

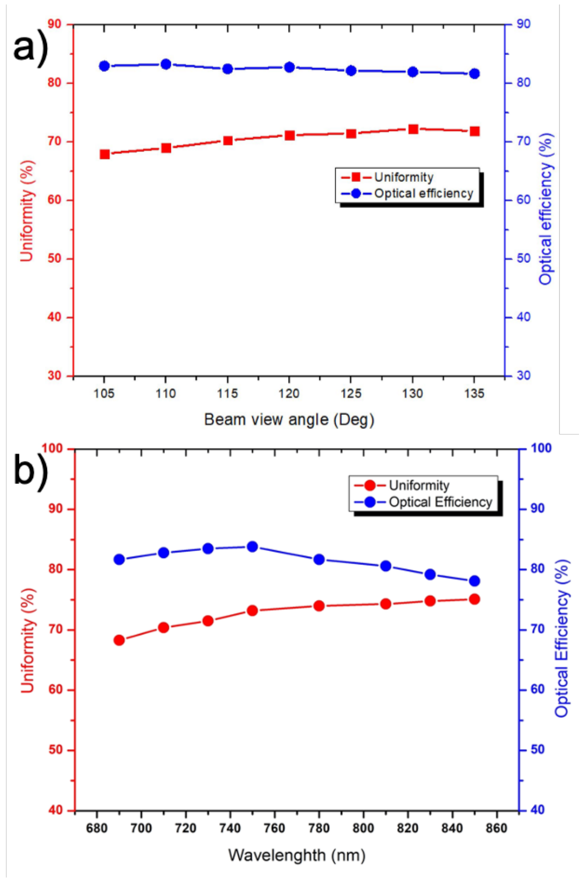

Fig. 13 The optical efficiency and Uniformity are functions of a) the beam view angle of LED and b) the wavelength emission of LED

The simulation of the flashlight source of the vehicle speed gun is conducted in LightTools™ with wavelength 750 nm and 3.000.000 rays. The results of the simulation process show that the distribution of light over the target area is quite uniform as illustrated in Fig. 12.

The uniformity *U* can be changed as a function of some parameters such as the distance of the light source and target area, the wavelength of the LED, and the interview beam angle of the LED. When the characteristics of LED in real conditions are different from the design parameters or the assembly of components is not perfect, all those aspects affect to uniformity and optical efficiency of the designed flashlight source for the vehicle speed gun. Therefore, the effect of those aspects was analyzed in LightTools™ to evaluate the ability to perform in real conditions.

Fig. 13 a) shows that the uniformity and optical efficiency of the designed collimator are independent of the change of beam view angle of LED from 105^0 to 135^0. This trend relates to the structure of each collimator lens. The structure of the collimator lens is divided into two parts the outer angle and the inner angle. In which the inner refraction part has a hole center that can cover all rays emitting from LED with a beam view angle smaller than 180^0. In this design, the rays with emission angles from LEDs smaller than 30^0 are guided by refraction at the front center entry to be a horizontal ray that will go forward to the target area. In addition, the rays with emission angle from LED greater than 30^0 are refracted and total internal reflected (TIR) to be parallel rays exiting the lens. Although the simulation results show that the beam view angle of LED does not affect much the uniformity and the optical efficiency of the collimator, the size of the light source will affect significantly the performance of the collimator lenses. However, the size of the emission area source is kept constant in this design because the LED characteristics are inserted from the library of LightTools™. This mention illustrates that the designed collimator lenses can be used with different LEDs with different beam view angles of emission beam of LEDs.

Fig. 13 b shows that the change in the wavelength of LED will affect the optical efficiency and uniformity of the collimator system. When wavelength changes leading to the refractive index of the medium lens (PMMA) will be changed, thus, the refractive angle of incident rays coming to the interface will also change. Depending on the wavelengths which are shorter or longer the exiting bundle of rays will be diverged or converged leading to uniformity and the optical efficiency will be changed. The optical efficiency changes slightly as a function of wavelength and reaches the maximum value at wavelength 750 nm which is chosen to design the collimator lens. The optical efficiency still reaches the value of about 80 % when the wavelength is 810 nm (infrared wavelength) which is suitable for the application of a vehicle speed gun. The optical efficiency of the collimator lenses can be changed following the change of wavelength; however, the change is slight with the sensitivity which is calculated by the ratio of change in optical efficiency and the change of wavelength that has the value of about 10 %. This analysis illustrates that the designed collimator lenses can be used with quite freely infrared LED sources. On the other hand, the uniformity tends to increase slightly because of the refractive index decreasing leading to the collimated beam diverging a little. The value of uniformity is always higher than 70 % in the range of analyzed infrared wavelength. This analysis illustrates that the designed collimator is suitable for different infrared LEDs. In another word, this designed collimator is not only suitable for PMMA materials but also it can be made with different materials for lenses. All aspects mentioned above show that the designed collimator can be carried out in actual conditions with an acceptable range of tolerance.

There are some studies about the determination of a car's speed in a nighttime as mentioned above. However, the approach of using infrared wavelength as a flashlight to take photos which are used as evidences of the car's speed over the limit velocity is a novel idea. The advantage of this approach is the structure of the conventional vehicle speed gun system does not need to be modified. A portable vehicle speed gun using the Dopler effect can be used in the nighttime, however, the photos for evidence issue should be solved. Therefore, using infrared LED as a flashlight for the aim of taking photos in a vehicle speed gun is a suitable method with minimum extended cost. Depending on the application, the unique design of the lens for the LED chip is necessary to guide the illumination energy to the target area to meet the requirements of the particular application. Therefore, to use effectively the infrared LED with a compact battery, the design of a collimator for the infrared LED in the LightTools™ library is proposed in this study. The design of the collimator is performed and simulated in LightTools™ to estimate the rationality and the performance when it is applied to a flashlight of a vehicle speed gun system.

Promising simulation results show the high potential to perform the proposed flash light assembled with a designed collimator to the vehicle speed gun to extend the ability of the traditional vehicle speed gun. The simulation results of the proposed collimator have been compared to other studies published before. The comparison illustrates the designed collimator is acceptable. In the design of collimators from Haobo et al. (Haobo 2015) and from Vidal et al. (Vidal 2014), the optical efficiency is about 80 % which is quite similar to that of the proposed collimator. However, both collimators have a distance from LED to target area short of about 5 m which is not suitable for the application of flash light of a vehicle speed gun. Moreover, the structure of these collimators is more complicated and bigger compared to the proposed system. These properties will negatively affect the portability of the vehicle speed gun.

Furthermore, the simulation results of the proposed collimator have been compared to that of studies from the research groups Chen *et al.* (2014) and Vu *et al.* (2017). In the research of Chen *et al.*, although the optical efficiency and uniformity are higher than that of the proposed collimator, the size and the divergent angle of the collimator lens are large which can make the flashlight bulky and have a negative effect on the utility of energy of the battery. In terms of the study from Vu et al. The optical efficiency is quite similar to that of the proposed collimator. However, the divergence angle is quite large of about 7.5^0 which can not apply to the flashlight of a vehicle speed gun with a long distance from the light source to the target area. The designed collimator in Vu et al. research is just suitable for illumination distribution with the collimator placed in front of the distributor lens. Based on these analyses, the comparison between collimators that are designed for different applications is difficult. However, all those analyzed aspects show the necessity of designing a particular collimator for infrared LED applied to a vehicle speed gun. Consequently, the simulation results obtained from the proposed collimator illustrate the conformity to apply to a flashlight of a vehicle speed gun. The simulation results also show a high potential to make a prototype to investigate the system in real conditions. All simulation results used for comparison are shown in Table 2. Additionally, Fig. 14 shows the shapes and structures of some collimators published already to have an overview of the comparison.

Table 2
The properties of the proposed system and other studies.

Properties\Studies	Proposed study	(Chen *et al* 2014)	(Haobo *et al* 2015)	(Vidal et al 2014)	(Vu *et al* 2017)
LED type	≥ 750 nm	CREE XR-E	Cree XP-E2	525 nm ±15 nm	White LED
Distance of target	30 m	Not mentioned	5 m	5 m	Infront of distributor
Diameter of collimator	21.5 mm	32.36 mm	17.12 mm	60 mm	10 mm
Type of collimator	Refraction and TIR	Refraction and TIR	Refraction and TIR	Refraction and reflection	Refraction
Optical efficiency	~ 80 %	89 %	79.2 %	80 %	~ 80 %
Uniformity	~ 71 %	78 %	Not mentioned	Not mentioned	Not mentioned for collimator
Divergence angle	< 2^0	2^0 and 4^0	3^0 - 13^0	< 2^0	7.5^0

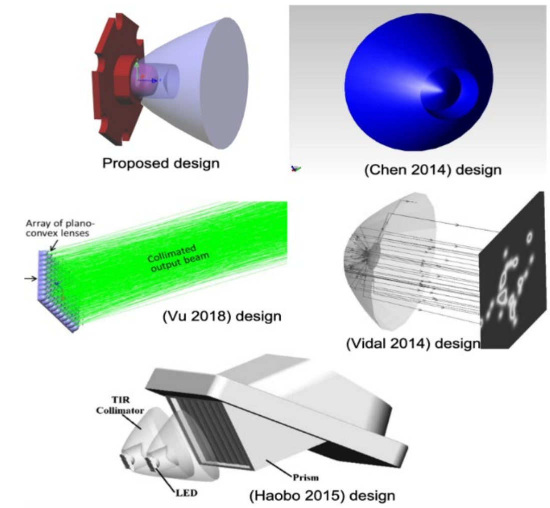

Fig. 14 The structure of some collimators compared to the proposed collimator

6. Conclusion

In this study, the design of the collimator in detail is introduced using non-imaging optics. The collimator system is a combination of many single collimators which is constructed in the Matlab program with some initial parameters for the design process such as the wavelength of 750 nm, materials for the lens of PMMA, etc. Two different structures of single collimator lenses are proposed, and after that, the characteristics of both are analyzed to choose the better structure. The chosen single collimator lens is structured consisting of two parts: the outer part uses refraction and total internal reflection to guide the ray entering the collimator while the inner part uses refraction to guide the rays coming to the front center entry interface. The size of each part is chosen freely using the beam view angles of emission rays from LED. In this design, the outer part and the inner part are separated at the angle of 30^0 beam view angle. A single lens is designed in the Matlab program, and after that, the data from Matlab is transferred to LightTools™ to draw three dimensions of the collimator. The 3D object in LightTools™ is added the optical properties to do the ray-tracing and simulation to evaluate the performance of the single collimator lens and the collimator system. The simulation results show that the designed collimator array can be carried out with different infrared LEDs. Furthermore, the collimator lens can be made from different materials without changing much of the performance of the collimator which is applied to a vehicle speed gun system. All analyzed aspects in this study illustrate the high potential of the collimator system combined with the infrared LED to apply a vehicle speed gun to increase the performance of the speed gun at nighttime performance. Although the study stops at the simulation in LightTools™, good properties of the designed collimator system motivate a plan to create a prototype to evaluate the performance of the designed collimator system in actual conditions soon. Based on simulation results in this study, a prototype of an illuminator to carry out a vehicle speed gun system in nighttime conditions is a promise. The simulation results are used to compare to other collimators that are designed by other research groups.

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