

Encapsulation shape with non-rotational symmetry designed for extraction of polarized light from unpolarized sources

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Abstract: A non-rotationally symmetric encapsulation shape – which takes advantage of the low reflection coefficient for transverse magnetic polarized light near Brewster’s angle – designed to enhance extraction of a particular desired linear polarization from an unpolarized source is reported. The algorithm for optimization of the shape is described. Numerical ray-tracing simulations of the encapsulation shape are performed and predict an integrated enhancement of 8.3% in the ratio of desired polarization to undesired polarization when the refractive index of the encapsulant is 1.5. Experimental measurements of fabricated encapsulant shapes agree well with numerical predictions.

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References and links

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1. Introduction

Polarized light sources are highly desirable for many applications including high-contrast imaging [1, 2], noise reduction in free-space optical communications [3], and liquid crystal display (LCD) backlighting [4-7]. In these applications, a single linear polarization is desired and the orthogonal polarization may be considered undesirable. However, semiconductor light-emitting diodes (LEDs) – which are attractive for many of these applications – are generally considered to be unpolarized sources, despite the polarization characteristics that can be present in unpackaged LED chips [8, 9]. The unpolarized nature of light emitted by

conventional packaged LEDs results from the design of secondary optics such as reflectors and encapsulation shapes. Here we demonstrate that the encapsulation shape used for an LED or any other light source can be designed specifically to increase extraction of a particular desired linear polarization.

In packaged devices, the LED chip is typically encapsulated with a transparent material that has a refractive index greater than that of air, which decreases the fraction of light generated in the high-refractive-index semiconductor that is trapped by total internal reflection. The encapsulation shape generally exhibits rotational symmetry; when used with an unpolarized source, a rotationally symmetric encapsulation shape results in equal output for both desired and undesired polarization. When only a single linear polarization is desired, however, encapsulation shapes without rotational symmetry can be designed to increase the extraction efficiency of the desired polarization.

2. Concept and algorithm for generating encapsulation shape

The principle of the polarization-enhancing encapsulation shape is based upon the low reflection coefficient near the Brewster angle for transverse magnetic (TM) polarized light. The cross section of the optimized shape is easy to visualize. Consider a light source with the encapsulation cross section as shown in Fig. 1. Above the light source in the xy -plane is a polarizer which allows x -polarized light to pass and blocks y -polarized light. For any ray that can be drawn from the light source to the encapsulation surface, the angle between the incident ray and the normal to the surface is the Brewster angle. Light that is polarized within the xz -plane – which can pass through the polarizer – is TM with regard to the surface and does not experience reflection when it strikes the interface because it is incident at the Brewster angle. Any encapsulation shapes where the incident angle is different from the Brewster angle will result in reflections for xz -polarized light and lower extraction efficiency. Light polarized in the y -direction – which is blocked by the polarizer – is transverse electric (TE) polarized with regard to the surface, and does undergo some reflection at the interface. Therefore, the encapsulation shape shown in Fig. 1 increases the extraction efficiency for the desired linear polarization when compared to a conventional encapsulation shape. As a result, light leaving the encapsulation will be partially polarized even when the light source itself is completely unpolarized.

The three dimensional optimized structure is numerically determined as follows. An unpolarized, isotropic point-like light source is assumed to be located at the origin. The point source approximation is valid as long as the surface area of the emitter is small compared to the dimensions of the encapsulation. Because of symmetry, it is sufficient to calculate only one quarter of the structure. The surface of the encapsulation is defined in terms of a rectangular grid of points in spherical coordinates in which the azimuthal angle θ and zenith angle ϕ for each point are fixed and spaced at regular intervals. The radial coordinate r is initially unknown. For the point directly above the light source, r is set equal to the unit length. A single line of points on the mesh for which θ is fixed is now calculated. For each point on this line other than $\phi = 0$, two new points $(\theta + \Delta\theta, \phi)$ and $(\theta - \Delta\theta, \phi)$ are considered. A triangle can be formed between the $\phi = 0$ point and the two new points with adjacent ϕ value. The calculation now considers an unpolarized beam which travels through the center of the three rays formed between the origin and the three triangle vertexes. The pair of r -values which maximizes transmission of this beam through a linear polarizer that lies in the xy -plane and allows light polarized in the x -direction to pass is found. Once r has been found for these two points, it is possible to form four distinct triangles between the two points with newly found r and the two points with the next ϕ value. The pair of r -values which simultaneously maximize transmission through the linear polarizer for beams traveling through the center of each of the four triangles is then found. This process continues until all the points on the line have been found. The values of r for the points (θ, ϕ) on the line are then found by averaging

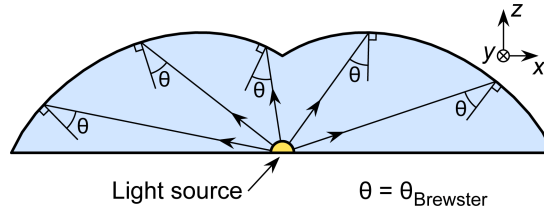


Fig. 1. Cross section of encapsulation shape which enhances extraction of a light polarized in the xz -plane. The angle between the normal to the surface and the incident beam in all cases is Brewster's angle.

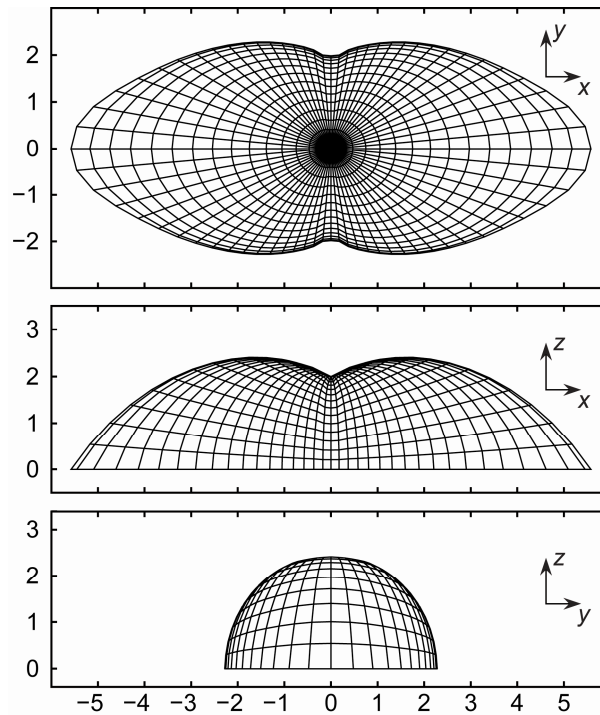


Fig. 2. Wireframe view of the polarization-enhancing encapsulation shape.

r for the points $(\theta + \Delta\theta, \phi)$ and $(\theta - \Delta\theta, \phi)$. This process is repeated until all the points on the mesh have been calculated. The entire encapsulation shape is formed by appropriately rotating and reflecting the known quarter structure. A wireframe view of the optimized encapsulation shape is shown in Fig. 2.

3. Ray-tracing simulations

Calculations to determine the effectiveness of the encapsulation shape were performed using LightTools optical engineering software, which uses ray-tracing with full optical accuracy to simulate optical systems. Simulations consider the encapsulation shape with a single point source located at the origin, centered at the bottom of the encapsulation. The refractive index of the encapsulation material is 1.5. The bottom of the encapsulation is covered with an absorbing material, which minimizes the effect of light rays that undergo multiple reflections. In order to determine the overall effectiveness of the encapsulation shape it is surrounded by a polarizer and detector; all light leaving the encapsulation strikes the polarizer and is either absorbed or transmitted; transmitted light reaches the detector. The polarizer can be controlled to allow x -polarized or y -polarized light to pass. The figure of merit used is the



Fig. 3. Photograph of a polarization-enhancing encapsulation shape

polarization ratio R_p , which is given by $R_p = P_x / P_y$. Here, P_x and P_y are the total optical powers which are transmitted through a polarizer allowing light polarized in the x -direction and y -direction, respectively, to pass. LightTools simulation results predict an overall enhancement in the polarization ratio of 8.3% for the optimized encapsulation. When the same structure is simulated with $n = 1.6$, the enhancement is 14.1%. The higher value for R_p is due to the increase in reflection for TE polarized light near the Brewster angle with increasing refractive index. Calculations of the intensity of x - and y -polarized light as a function of angle are also performed in order to form a comparison between predictions by LightTools and measurement results of fabricated encapsulation shapes, which will be discussed in Section 5.

4. Experimental methods

The encapsulation shape is experimentally realized by fabricating an aluminum mold with a computer controlled milling machine and then extensively polishing the mold to achieve a specular optical surface. A two-component epoxy intended for optics applications is poured into the mold and then cured at 120° C for 2 hours. Figure 3 shows a photograph of the fabricated encapsulation shape.

For experimental measurements, the light source is formed by a mixture of yellow phosphor and epoxy that is embedded centered at the bottom of the encapsulation. The phosphor is optically excited by a high power blue LED. The LED-excited phosphor is selected as a source because it allows simple index matching between the source and encapsulant, and because the light emitted by the phosphor is completely random in polarization. Using an unpolarized phosphor source rather than an LED – which can exhibit some polarization characteristics – simplifies verification that the encapsulation shape is working as intended.

A schematic of the measurement setup is shown in Fig. 4. The encapsulation with embedded phosphor is located at the axis of rotation for an arm which holds a 533 nm filter, linear polarizer, and photodetector. The arm can be rotated about the light source to measure the intensity as a function of the zenith angle ϕ . The backside of the encapsulant is masked with the exception of a small square less than 0.5 mm wide so as to reveal only the phosphor; together with the 533 nm filter, this ensures that only light generated by the phosphor is measured. The mask also serves to eliminate multiple reflections inside the encapsulant, which aligns the experimental setup with the simulations performed in LightTools and should give better agreement with calculated predictions. However, in practice it would be desirable to introduce a reflector at the base. For example, if a diffuse reflector is used, then light with the non-desirable polarization – which has a stronger initial reflection – will be randomized in polarization and direction when it strikes the reflector, and will contribute to the intensity of the desired polarization when it escapes the encapsulant.

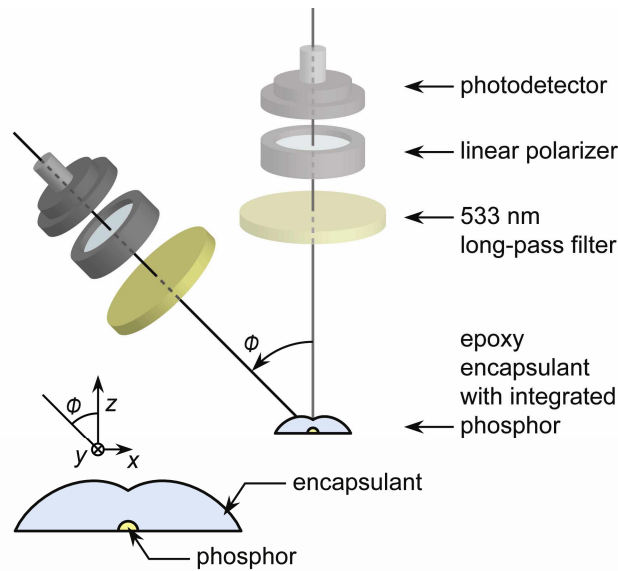


Fig. 4. Depiction of setup used for measuring the polarization-enhancing encapsulant. The measurement arm rotates about the y -axis and remains in the xz -plane.

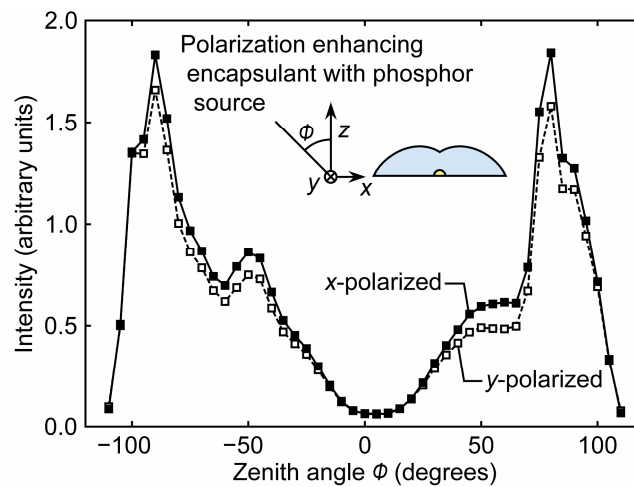


Fig. 5. Intensity of x -polarized and y -polarized light as a function of the zenith angle ϕ .

5. Results and discussion

Figure 5 shows the measured intensity as a function of the angle when the polarizer is oriented in the x -direction and when the polarizer is oriented in the y -direction. The intensity is low for $\phi = 0$ and becomes larger as the magnitude of ϕ increases. This is because the encapsulation shape also acts as a lens which focuses the light produced by the phosphor in specific directions. In Fig. 5, the intensity of x -polarized light is consistently higher than that of y -polarized light throughout the range of angles measured. Figure 5 also reveals an asymmetry in the intensity as a function of angle. This difference is likely due to an asymmetry in the encapsulant shape itself; the fabrication method used relies heavily on work done by hand, and does not produce a perfect result. Subtle differences between two sides of the encapsulation shape can produce a difference in the farfield intensity distribution and in the intensity as a function of angle. Figure 6 shows the ratio of the two intensities

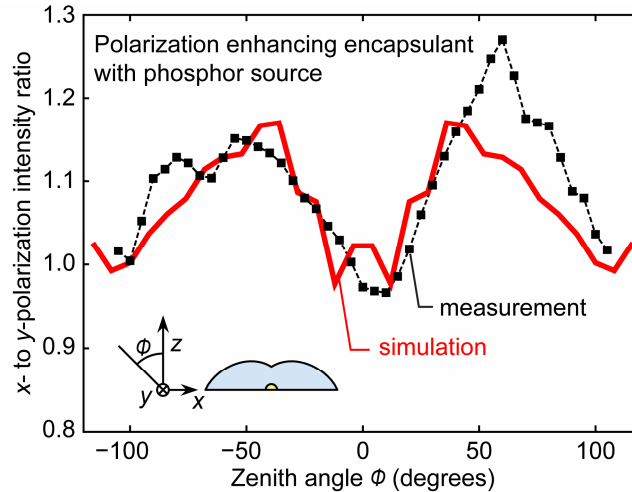


Fig. 6. Intensity ratio of x -polarized light to y -polarized light as a function of the zenith angle ϕ

as a function of angle and provides a comparison with the numerically simulated result. The measured curve in Fig. 6 is again somewhat asymmetric; this is related to the asymmetry of intensity in Fig. 5 and is attributed to imperfections in the fabricated encapsulation shape. The measured ratio is greater than unity for all angles other than those close to $\phi = 0$, where the actual intensity is very low. For angles where the intensity is high, the polarization ratio becomes larger than unity. The shape of the measured curve matches the shape predicted by numerical ray-tracing simulations. However, the peak measured value is approximately 1.28, which is higher than the peak calculated value. This difference can be attributed to a discrepancy between the actual epoxy refractive index and the refractive index used in the calculations. As mentioned earlier, an increase in refractive index results in a larger polarization ratio for the same geometrical structure.

6. Conclusion

In conclusion, a non-rotationally symmetric encapsulant shape has been shown to enhance the extraction of a particular linear polarization from an unpolarized source by both numerical ray-tracing simulations and experimental measurements. The encapsulant shape takes advantage of the low reflection coefficient for TM polarized light at the Brewster angle and results in an overall theoretical enhancement of 8.3% when the refractive index is 1.5. The measured enhancement as a function of angle agrees well with calculated curves, while the magnitude is somewhat larger than the simulated result.

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