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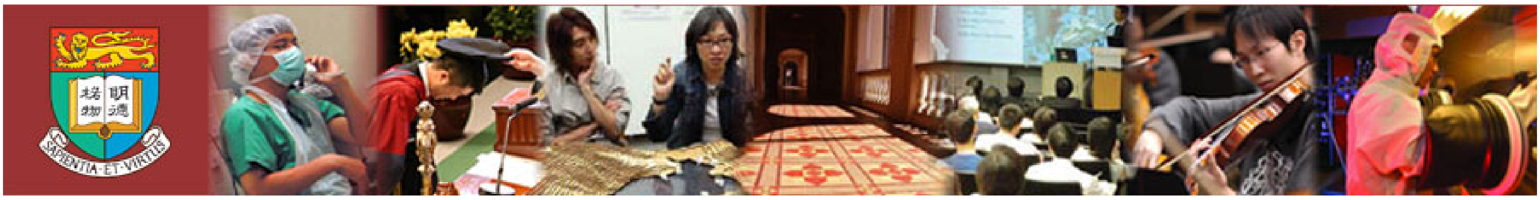

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Fiber-Coupled Light-Emitting Diode With a Capillary-Bonded Hemispherical Lens

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***Abstract*—A hemispherical lens capillary-bonded to an InGaN flip-chip light-emitting diode (LED) is demonstrated to efficiently couple light to a plastic optical fiber. The BK-7 hemispherical lens is bonded onto a circularly shaped LED chip with inclined sidewalls cut by laser-micromachining, so that lateral emissions are effectively suppressed. Capillary bonding minimizes air-gap between chip and lens enabling transmission of evanescent waves, thus maximizing overall optical transmission. With the lens attached, emission divergence from the assembly is significantly reduced, diverting rays into the acceptance cone of the fiber. Fiber coupling efficiency as high as 53.8% has been demonstrated.**

***Index Terms*—Fiber coupling, light-emitting diode (LED).**

I. Introduction

FIBER-COUPLED light sources are commonly adopted in a wide range of applications including microscopy, spectroscopy and optical communications, using different types of light sources. Coupled to broadband tungsten halogen or deuterium bulbs, the light carried on fiber can be used for microscopy illumination, ultraviolet curing, fluorescence excitation [1] or biological photo-stimulation [2] amongst others. However, due to the large dimensions of such light sources compared to a fiber, coupling efficiencies are invariably lower than 10%. On the other hand, the narrow divergence and high directionality of laser beams makes them particularly suitable for efficient coupling to fibers [3]; fiber-coupled laser diodes are thus widely used in optical communication systems [4]. Light-emitting diodes (LED) are miniature light emitters that are rapidly replacing conventional light sources, characterized by high quantum efficiency, quick response time, robustness and long lifetimes amongst its long list of attributes, and have become popular choices for panel displays, liquid-crystal display (LCD) backlights and gradually general lighting. Being light emitters of small footprint that emit with relatively wide divergence, how suitable are LEDs for fiber coupling?

Fiber (butt) coupling efficiency, η, depends mainly on (i) relative dimensions of light source and fiber; (ii) divergence of light source (iii) numerical aperture of fiber and (iv) distance between light source and fiber. Based on condition (i), LEDs, with dimensions similar to those of fiber, are ideal coupling sources. Nevertheless, the omni-directional emissivity of LEDs means that only light emitted from one emission surface of the chip fall within the acceptance cone of the fiber. With traditional light sources, the use of parabolic reflections and focusing optics can improve η. For a light source as small as an LED, the best strategy is probably to minimize the distance between the LED and fiber. Based on a simple electromagnetic wave (EM) model, η from a 1 mm $\times$ 1 mm LED with 120° full-width-at-half-maximum (FWHM) divergence into a 2-mm-diameter fiber with NA $= 0.4$ is $\sim$15% at 0.1 mm separation distance, and η falls off quickly with increasing gap. Reducing divergence with optics, whilst maintaining minimal separation, is thus the key to boosting η. However, the inclusion of external optics incurs additional free-space and interface losses which cannot be neglected. In this letter, a high-efficiency fiber-coupled LED structure is proposed, achieved through geometrical shaping of the chip and integration of hemispherical optics via liquid capillary bonding. The chip is designed to promote emission from the top surface; the hemispherical lens helps to reduce the emission divergence, while liquid capillary bonding minimizes Fresnel losses between chip and optics and enhance transmission of evanescent waves along the interface. Overall, beam coupling to fiber can be maximized.

II. Experimental Details

The LED chips used in this work are fabricated by standard micro-fabrication processes on GaN/sapphire wafers containing InGaN/GaN quantum wells, emitting at a central wavelength of 470 nm. After device fabrication, the wafer is lapped down to $\sim$ 200 μm and the LED chips are diced and shaped into truncated-conic structures (TCs) by ultraviolet (UV) nanosecond laser micro-machining. Chips of circular geometry emit circular beams [5], enabling maximum coupling with optical fibers which are invariably circular. Additionally, by coating a metallic layer onto the inclined sidewall, an integrated reflector is formed which suppresses lateral emissions effectively. Such 3-D structures are formed with a modified laser micromachining setup, by deflecting the laser beam with a turning mirror so that it is incident onto the wafer at an angle of $\sim$ 25° to the normal, and rotating the LED chip about its central axis. Further details of the laser processing can be found in [6]. The shaped chip with top and bottom diameters of 1.7 mm and 1.3 mm is then flip-chip bonded onto a ceramic package, referred to as a TC-LED, which is shown in Fig. 1(a). Without bond wires, the entire sapphire surface is exposed, on which a 2 mm diameter BK-7 hemispherical lens is attached via liquid capillarity [7]. The surfaces to be bonded must be optically flat (of better than 1/10 wave), achieved by precision polishing.

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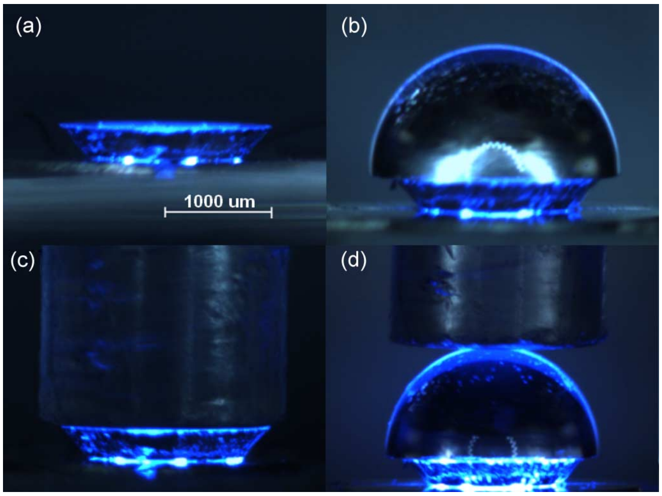

Fig. 1. Microphotographs showing (a) truncated-conical TC-LED; (b) hemispherical-lens-attached HL-LED; (c) TC-LED coupled to a POF; and (d) HL-LED coupled to a POF.

The hemispherical lens was dipped in acetone and brought into contact with the sapphire surface; a force is applied to press them together. As the solvent evaporates, the chip and lens are pulled towards each other via liquid surface tension. The drying process can be monitored by observing the evolution of interference fringes. When the interface is free of fringes, the bonding process is complete and a tight bond is established. Being a manual process, the alignment tolerance is $\pm 100\ \mu$m. The assembly, referenced to as HL-LED in this work, is shown in Fig. 1(b). For reference, an identical TC-LED is prepared, without attachment of a hemispherical lens. Optical transmission across a capillary-bonded interface is investigated both experimentally and numerically. Optical characteristics of the prepared LEDs are measured. Finally, the beams from the LEDs are coupled to 2 mm-diameter plastic optical fiber (POFs) with an NA of 0.5, and the coupling efficiency evaluated.

III. Results and Discussion

The proposed LED assembly is expected to excel due to three major factors: (a) chip geometry; (b) hemispherical lens and (c) liquid capillary bonding. The combination of (a) and (b) is meant to narrow down the divergence of the emitted beam [8]. To determine the success of this design, the two-dimensional far-field radiation patterns of the LEDs biased at 20 mA are measured using a goniometric setup, as plotted in Fig. 2. As observed from the plot, the FWHM of the HL-LED is effectively reduced to $\sim 70^\circ$ compared to $\sim 120^\circ$ for the TC-LED. The lens-integrated device also demonstrates an overall increase in light extraction efficiency. The total emission optical powers, as measured by a radiometric-calibrated spectrometer via a 2-inch integrating sphere, are 3.50 mW and 3.09 mW for the HL-LED and TC-LED respectively. This can be attributed to the hemispherical lens, which serves as both an index matching medium and focusing optics. The focusing ability is demonstrated from the emission intensity in the vertical direction, which has been enhanced by 57.5%. The reduced divergence and enhanced optical power in the normal direction suggest that more light can

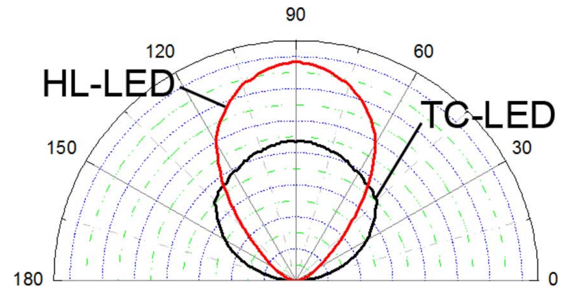

Fig. 2. Polar plots showing angular-resolved emission patterns of TC-LED and HL-LED.

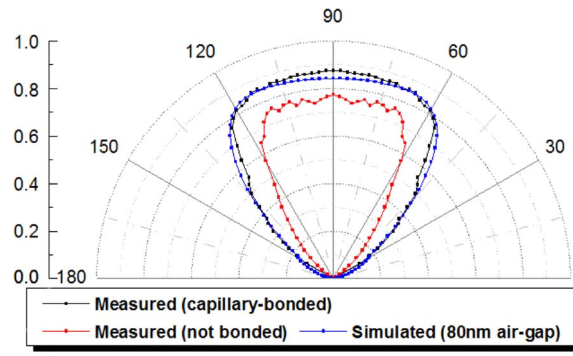

Fig. 3. Measured and simulated angular-resolved transmission plots across a sapphire/BK-7 interface at different air-gap distances.

be coupled to a fiber, since more emitted light rays fall within the acceptance cone of a fiber.

Capillary bonding of the lens also plays a role in producing such performance figures. An experiment is carried out to investigate optical transmission across a capillary-bonded interface between a 1-mm-thick BK-7 window and a 500 μm-thick sapphire window. An incident 473 nm beam from a diode-pumped solid-state (DPSS) laser strikes the sapphire face of the assembly at varying incident angles, and the transmitted beam collected by a calibrated Si photodetector from the BK-7 side. The angular-resolved transmittance is obtained by comparing the transmitted optical power with the emitted optical power at intervals of 2°, plotted in Fig. 3 represented by the black curve. For reference, an identical BK-7/ sapphire window assembly without capillary bonding is prepared. Transmittance data across this unbonded assembly is represented by the red curve in Fig. 3. Comparing the respective plots, transmittance across the capillary-bonded interface is enhanced.

To better understand the mechanism involved, a simplified electromagnetic model is adopted to study air-gap effects on optical transmittance. In this model, the light source is simply modeled as a dipole with horizontal oscillation; transverse magnetic (TM) waves propagating on the xz-plane are studied. Although light is generated from the GaN layers, it is extracted from the device through sapphire due to the flip-chip geometry. The model consists of 5 regions, namely air, 500 μm sapphire, air-gap of varying thickness, 1000 μm BK-7 and air. The dipole, oscillating $\lambda = 475$ nm, is placed 10 nm from the air/sapphire interface, while the observation point is 100 mm from the BK-7/air interface, so that lateral light from edges of the BK-7 plate can be neglected. Additionally, both sapphire and BK-7

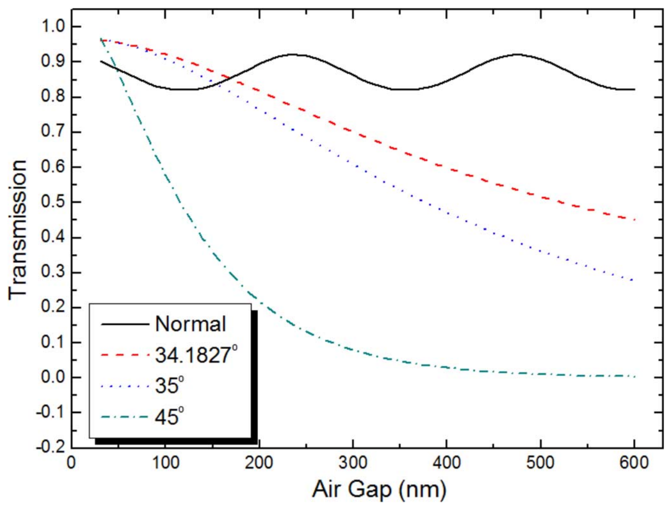

Fig. 4. Calculated transmittance across a sapphire/BK-7 interface versus air-gap distance at angles of 0° (normal), 34.1827° (critical angle for evanescent wave), 35°, and 45°.

are considered transparent at the wavelengths of interest. For TM waves, magnetic fields (H-fields) in each layer can be expressed as [9],

$$\overline{H}_l = \widehat{y}(F_l e^{ik_{lx}x} + B_l e^{-ik_{lx}x})e^{ik_z z} \quad (1)$$

where F_l and B_l are amplitudes of the forward and backward waves, while k_{lx} and k_z are x, z components of wave vector at the $(l+1)$-interface ($l = 0$, 1, 2, 3). The reflectance R can be estimated using the recursive expression:

$$\frac{B_l}{F_l} = \frac{R_{l(l+1)}e^{i2k_{(l+1)x}d_l} + (B_{l+1}/F_{l+1})}{e^{i2k_{(l+1)x}d_l} + R_{l(l+1)}(B_{l+1}/F_{l+1})}e^{i2k_{lx}d_l} \quad (2)$$

$$R_{l(l+1)} = \frac{n_{(l+1)}^2 k_{lx} - n_l^2 k_{(l+1)x}}{n_{(l+1)}^2 k_{lx} + n_l^2 k_{(l+1)x}}, \quad (3)$$

from which the electric fields can be obtained. Comparing transmitted and incident energies, the calculated transmittance at 0° (normal), 34.1827° (critical angle for evanescent wave), 35° and 45° are plotted in Fig. 4. At normal incidence and at angles below the critical angle, the propagation constant is real and thus only carries phases. The transmission curve is thus oscillatory in nature corresponding to the relative phases of the incident and reflected waves, oscillating in the range of ~80 to 90%. Within this range, the effect associated with capillary bonding is negligible. At the critical angle, transmission drops rapidly with increasing gap width as the propagation constant becomes complex; however evanescent waves can only propagate across very narrow boundaries. The rate of decrease in transmission is also seen to grow with increasing incident angle. As such, one can appreciate the effectiveness of minimizing gap width via capillary bonding. The curve plotted in blue of Fig. 3 represents a simulated angular transmittance plot for the case of 80 nm air gap; the close resemblance to the measured data for the capillary-bonded assembly indicates that the actual air-gap achieved with capillary bonded can be as small as ~80 nm.

To determine fiber coupling efficiencies, light emitted from the LEDs is coupled to a 10-feet POF ($\mathrm{NA} = 0.5$), illustrated in Figs. 1(c) & (d). The fiber is mounted onto a three-axis micro-positioner for precise alignment ($\pm 5\ \mu$m) to capture as much light as possible from the devices. The coupling efficiency is determined by comparing the optical power at the terminal end of the fiber with that emitted by the LED, neglecting attenuation along the fiber. The maximum coupling efficiency achieved with the HL-LED is 53.8%, compared to 30.2% from the TC-LED, representing a significant increase of 78%, signifying the effectiveness of the proposed approach for assembling a fiber-coupled light source.

IV. Conclusion

With a capillary-bonded hemispherical lens, an LED assembly is demonstrated to offer a fiber-coupling efficiency of 53.8%. The enhanced efficiency can be attributed to a combination of three factors: chip geometry, focusing capability of the lens and the method of lens attachment. The chip was shaped into truncated conical structures with metal-coated sidewalls, ensuring emission from the device top surface. The hemispherical lens diverts rays to a focus point at which the fiber is placed. Capillary bonding of the lens to the LED chip minimizes free-space losses and promotes transmission of evanescent waves, contributing to high overall optical transmission across the interface.

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