LEDs and Doped Polymer Light Guides for Efficient Illumination and Colour Engineering

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Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree, nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

C. A. Deller

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Jim Franklin derived the theory of deviation of a TRIMM sphere, and assisted with the basic concepts of spherical trigonometry and probability functions. He also suggested the method for measuring TRIMM concentration in matrix materials, and the method for measuring 'luminous flux half angle' of the LEDs.

All of the experimental and simulated results presented in this thesis are my own work.

I developed all computer programs, using Mathematica®software. This was no small feat since I had previously received very little relevant training, having attempted only short, rudimentary programming exercises. I therefore do not claim that the coding style is the most elegant that has ever been written.

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Glossary of Symbols and Acronyms

(X, Y, Z)	direction cosines of a ray
(x_0, y_0, z_0)	Cartesian coordinates of the starting point of a ray, or the starting point for propagation in a new ray direction
(x_1, y_1, z_1)	next interaction point of a ray (particle or guide wall)
(X_i, Y_i, Z_i)	CIE tristimulus values
(x_i, y_i, z_i)	CIE colour coordinates for a pixel of the output light distribution
$(x_{LED}, y_{LED}, z_{LED})$	CIE colour coordinates for a LED
a	axial particle number (the number of particles intercepted by a straight line drawn through a TRIMM-doped light guide, parallel to the optic axis)
CCD	charge coupled device
CCT	colour correlated temperature
CIE	Commission Internationale de L'Eclairage
CRI	colour rendering index
EPA	1-ethoxy-2-propyl acetate
ESEM	environmental scanning electron microscope
F	exponential decrease of side-scattered output light with distance along a TRIMM-doped light guide
$f(\delta)$	the probability density distribution of the deviation $\delta(h)$
h	impact ratio, $h = H/r$. h is independent of sphere radius.
H	perpendicular separation distance (of a ray impacting a sphere) from the parallel ray passing through a sphere's centre ($H = r-\lambda$ at the geometric limit)

HID	high intensity discharge (lamp)
i	projection of *l'* onto the x-y plane
I	light intensity (or in some cases, luminance)
IR	infra-red
l	propagation length of a ray between two particular particles
L	Length of a light guide (generally in cm)
LCD	liquid crystal display
LED	light-emitting diode
l'	length from a particle to the light guide wall, if the wall is intercepted before the following particle is reached
m	relative refractive index (usually the ratio of particle refractive index to that of the matrix in which the particles are dispersed)
m_f	mass fraction (of spheres in a matrix)
MMA	methylmethacrylate (monomer)
NA	numerical aperture (of a light guide)
n_i	refractive index of component *i*, such as TRIMM sphere or light guide matrix
p	average path length travelled by a ray between particle interactions
P(h)	the integrated probability density distribution (for unit TRIMM sphere radius)
$P(\theta)$	cumulative probability density function (for empirical LED source models)
PMMA	polymethylmethacrylate
POF	(flexible) polymer optical fibre
r	radial distance of (x_0, y_0, z_0) from the z-axis in the x-y plane (ray tracing context)
r	particle radius (e.g. of a TRIMM sphere)
R	radius of a cylindrical light guide
R	Fresnel reflectance

RGB	red, green, blue
RI	refractive index
$S(\lambda)$	spectral power distribution (of a LED)
SPD	spectral power distribution
SRF	source radial fraction (position of a LED at the entrance end of a mixing rod, relative to the optical axis the rod)
T	transmittance
TIR	total internal reflection
TRIMM	transparent refractive index matched micro-particles
UTS	University of Technology Sydney
UV	ultraviolet
V_f	volume fraction (of particles in a matrix)
$\bar{\Sigma}$	mean half-cone angular spread of light in the cross-sectional plane of a light guide
α	reflection angle of a ray from the light guide wall in the x-y plane (ray tracing context)
α	linear particle density (number of particles per metre intercepted by a straight line drawn through a TRIMM-doped light guide, parallel to the optic axis)
χ	'glancing angle' between a ray and the wall of a cylindrical light guide
χ_n	angle between a ray and the normal to the light guide wall
δ	semi-cone angular component of a ray's deviation, relative to the previous direction of the ray
$\bar{\delta}$	mean deviation angle of the probability density distribution of the deviation $f(\delta)$
δ_{geom}	deviation angle at the geometric limit

δ_m	median deviation angle of the probability density distribution of the deviation $f(\delta)$
$\delta(h)$	general expression for deviation angle of a ray impacting a TRIMM sphere, in terms of the impact ratio h
ε_1	azimuth component of a ray deviation
ε_2	difference (in angle) between ϕ_2 and ϕ_1
ϕ	azimuth component of a ray rotated about the z-axis, with $\phi = 0$ at the x-axis
ϕ_1	initial ϕ component of a ray (within a light guide)
ϕ_2	ϕ component of a ray after angular deviation by a particle
$\phi_{reflect}$	new ϕ direction after reflection from the light guide wall
ϕ_t	ϕ in the translated reference frame (rotated by τ)
ϕ_{tr}	reflected ϕ in the translated reference frame
γ	angle between r and the x-axis
φ	azimuth angle of a ray relative to the plane containing both r and the z-axis
λ	wavelength of light
m	difference of the relative refractive index m from 1
θ	semi-cone angle of a ray with the z-axis (light guide axis) within the matrix of the light guide
θ_1	initial θ direction of a ray (within a light guide)
θ_2	θ direction of a ray after angular deviation by a particle
θ_s	angle-of-incidence of a ray impacting a TRIMM sphere
τ	angle between R and the x-axis

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Abstract

This project involves the study of optical properties of polymers doped with TRIMM (transparent refractive index matched micro-particles), and their uses in light guides. The refractive index difference between dopant and host material is small (<0.02), so forward transmittance is high, and losses due to backscattering are negligible. Flexible polymer optical fibre (POF) and polymethylmethacrylate (PMMA) rods are being incorporated into an increasing range of lighting and light mixing applications. For energy efficient mixing of red, green and blue (RGB) light-emitting diodes (LEDs) to produce white light and a range of other colours, light is transmitted from the end of a light guide ("end-light"). A major problem here is solved, namely the achievement of uniform illumination, simultaneously with low losses from scattering. Light output from RGB LEDs is shown to be completely mixed by short TRIMM-doped light guides. Alternatively, long lengths of TRIMM-doped POF can be used for "side-light". The concentration of TRIMM for these is chosen such that light is emitted from the side walls of the guide to give even illumination along its length.

A geometrical method of ray tracing in particle-doped rectangular and cylindrical light guides is derived, and Monte Carlo ray tracing simulations performed for undoped and TRIMM-doped light guides. The evolution of the distribution of ray angles, internal and external to a light guide, with propagation distance are studied. Computer simulations of angular distribution of light emitted from the wall of POF agree with measurements performed using a photogoniometer.

Simulations and measurements of light output intensity and colour from RGB LED arrays when projected from the end of a mixing rod, are also presented. Colour calculations agree with photometric measurements of RGB LED output from clear and TRIMM-doped PMMA mixing rods. Results of transmittance measurements and computer simulations show that light losses are almost entirely due to Fresnel reflectance from the entrance and exit surfaces of the rods.

Photogoniometer measurements of the angular distribution of light from LEDs are used as a basis for LED source models used in ray tracing simulations. Results of an investiga-

tion comparing the effect of using a smoothed LED source model instead of measurement-based models on simulated light output distributions are presented. The light output from LEDs can have sudden peaks in intensity at certain angles, resulting in distinctive patterns with clear colour separation, after mixing in clear polymer mixing rods. These caustic patterns are eliminated by using TRIMM-doped mixing rods, with a transmittance of ~90% after Fresnel losses, which can be readily reduced.