Light Generation, Transport, Mixing and Extraction in Luminescent Solar Collectors

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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 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.

Jim Franklin

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I developed all of the mathematical theory of the thesis except for section 7.2, which was developed jointly with Dr Paul Swift and Prof Geoff Smith, with the largest contribution being made by Dr Paul Swift.

I designed all of the experiments described in this thesis except those of section 5.4.1 (jointly designed with Chris Deller) and chapter 10 (jointly designed with Dr Alan Earp).

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Author's Publications

Parts of this thesis have been published in the journal articles, peer reviewed conference proceedings, granted patents and patent applications listed below. This thesis is unusual in that a substantial portion of the work was first published as patents. There are a number of problems in how to cite these patents. See Appendix 2 for a discussion of the problem and the conventions adopted.

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GLOSSARY OF SYMBOLS AND ACRONYMS

(x, y, z)	Cartesian coordinate system with an origin at the centre of the entry face of a flat-to-round converter
(θ, ϕ, l)	Spherical coordinates

Roman Symbols and Acronyms

a	Aspect ratio of a sheet [m]
a	Axial particle number (the number of particles intercepted by a straight line drawn through a TRIMM-doped system parallel to the optic axis) [m^{-1}]
A	Cross sectional area of the optical system [m^2]
A	Absorbance of an optical system
A	Area of a source [m^2]
$\overline{A}$	Mean absorption fraction of light entering an LSC
dA	An infinitesimal area [m^2]
$\mathbf{dA}$	Vector associated with an infinitesimal area, dA [m^2]
$A(\lambda)$	Absorption spectrum
A_{eff}	Effective collection area of an LSC [m^2]
$A_{extractor}$	Area of the exit face of a hybrid LSC-LED light extractor [m^2]
A_{LED}	Area of individual LED chips in hybrid LSC-LED light extractor [m^2]
B	Fraction of total lumens from hybrid LSC-LED light extractor provide by the LED's
$BRDF$	Bidirectional Reflectance Distribution Function [sr^{-1}]
$c_o(z)$	Transverse curvature of the outer surface of a flat-to-round converter at distance z from the entry face [m^{-1}]
C	Contrast ratio between specular and diffuse light
$\mathbf{C'}_o(z)$	Position of the centre of the transverse curvature of the outer surface of a flat-to-round converter which has been adjusted so that the intersection of the outer surface with the y-z plane is a straight line [m]
$\mathbf{C}_i(z)$	Position of the centre of the transverse curvature of the inner surface of a flat-to-round converter at distance z from the entry face [m]
$\mathbf{C}_o(z)$	Position of the centre of the transverse curvature of the outer surface of a flat-to-round converter at distance z from the entry face [m]
d	Diameter of an inflated tube [m]
$D(\delta)$	Divergence of a TRIMM microsphere i.e. the ratio of the intensity of light scattered by a TRIMM particle at angle δ to the illuminating beam with the intensity of light scattered in the same direction as the illuminating beam
DABCO	1,4-diazabicyclo-[2.2.2] octane, a useful antioxidant
$E_C(\lambda)$	Measured spectrometer signal from the end surface of a clear sheet [counts]
$E_D(\lambda)$	Measured spectrometer signal from the end surface of a dyed sheet [counts]
E_e	Total power emitted by dye molecules [W]
EPO	European Patent Office
$E_x(\lambda)$	Spectral intensity at the side of an LSC at lateral distance x [$counts.sec^{-1}$]
f	Matrix loss factor (the fraction of the light lost in the clear reference sheet due to matrix extinction and Fresnel reflection at the far end).
$f(\delta)$	Probability density distribution of the ray's angular deviation [rad^{-1}]

f_{cone} Fraction of fluorescently emitted light in each escape cone

$f_{diffuse}$ Fraction of light in a hybrid LSC-LED light extractor that is diffuse rather than specular

f_{edge} Fractional loss of light in a flat-to-round converter due to scattering from rounded sidewall edges

f_{end} Fraction of fluorescently emitted light that is endlight (includes the correction for reflection at a LSC sheet's end mirror)

f_{escape} Fraction of fluorescently emitted light in combined escape cones

f_{geom} Fraction of rays striking a TRIMM microsphere that are within the geometric limit i.e. the fraction of rays that are well approximated by geometric optics

f_{scat} Fractional loss of light in a flat-to-round converter due to scattering off rough sidewalls

$f_{trapped}$ Fraction of fluorescent emission that reaches the a LSC's exit surface in the form of *F* Output luminous flux from an LSC [lm]

F Output luminous flux from an LSC [lm]

F_{all} The ratio of the total amount of light reaching a LSC's exit surface (i.e. the sum of endlight and trapped light) to the endlight

F_{in} Flux of a collimated light beam illuminating an annulus on a TRIMM microsphere [W]

F_l Luminous flux at the collection edge when LSC is illuminated at a plane of constant distance, *l,* from the collection edge [lm]

F_L Luminous flux at collection edge when LSC of length *L* is illuminated uniformly [lm]

F_o Luminous flux of the fluorescent test lamp [lm]

FSL Fluorosolar Systems Ltd

g_{max} Maximum possible étendue per unit area [sr.m^2]

G Étendue [sr.m^2]

G_{gap} Étendue of light at an air gap [sr.m^2]

G_{limit} Smallest value of the limiting étendue in an optical system [sr.m^2]

G_x^{max} Maximum possible étendue at cross section *x* [sr.m^2]

h Impact ratio, *h = h/r. h* is independent of the microsphere's radius, *r*

h_{geom} Impact ratio for the geometric limit, i.e. the impact ratio beyond which Mie theory is required to calculate the scattering pattern

H Perpendicular separation distance of a ray impacting on a microsphere from the parallel ray passing through a sphere's centre. [m]

HDPE High Density Polyethylene

$i(\delta,l)$ Intensity of the light scattered by a single TRIMM microsphere measured at distance *l* from the sphere and a deviation angle of *δ* from the illuminating light beam [W.m^{-2}]

I Average number of interactions of light with the sidewalls of a flat-to-round converter

I The point on the inner sidewall edge of a flat-to-round converter corresponding to point P on the outer surface [m]

$I(\delta)$ The intensity light scattered by a TRIMM microparticle at a deviation angle of *δ* to the illuminating beam, measured inside the host material [W.m^{-2}]

I_{in} Intensity of a collimated light beam illuminating a TRIMM microsphere [W.m^{-2}]

I_0 The intensity light scattered by a TRIMM microparticle in the direction of the illuminating beam, measured inside the host material [W.m^{-2}]

INPADOC International Patent Documentation Center

I_{sol}	Solar luminous intensity incident on the top surface of the collector [lux]
k	A proportionality constant for the fitted variation of the mean half-cone angular spread, $\overline{\Sigma}$, with the axial particle number, *a*
l	Length of a sheet [m]
l	Linear distance between point of illumination and collection edge [m]
l	Path length of a ray inside a light guide [m]
L	Length of a light guide [m]
L	Length of a clear reference sheet or collector sheet [m]
L	Radiance of a source [$W.m^{-2}.sr^{-1}$]
$L_{½}$	Half-length i.e. the path length over which 50% of the fluorescently emitted light is lost due to extinction [m]
L_{crit}	Critical length of a TRIMM doped mixer rod i.e. the length where the mean half-cone angular spread of the light is equal to the material's critical angle [m]
$L_{d½}$	Half-length contribution from the collector sheet's dye [m]
$L_{diffuse}$	Diffuse radiance of a skylight or LED-hybrid luminaire interpolated to the angle of maximum radiance [$W.m^{-2}.sr^{-1}$]
LDPE	Low Density Polyethylene
LED	Light Emitting Diode
$\overline{L}_{extractor}$	Mean radiance from a hybrid LSC-LED light extractor [$W.m^{-2}.sr^{-1}$]
$L_{g½}$	Half-length contribution from collector sheet's geometry [m]
L_{LED}	Radiance of the LED's in a hybrid LSC-LED light extractor [$W.m^{-2}.sr^{-1}$]
L_{local}	Radiance of the diffuse component of a system's output measured near the specular component [$W.m^{-2}.sr^{-1}$]
$L_{m½}$	Half-length contribution from collector sheet's matrix [m]
L_{max}	Maximum radiance of the specular component of a system's output [$W.m^{-2}.sr^{-1}$]
$L_{proj\ image}$	Radiance of the a mixer in a LED projector near the specular beam [$W.m^{-2}.sr^{-1}$]
$L_{proj\ specular}$	Radiance of the specular beam from a mixer in a LED projector [$W.m^{-2}.sr^{-1}$]
LSC	Luminescent Solar Collector
$L_{specular}$	Maximum specular radiance of a skylight or LED-hybrid luminaire [$W.m^{-2}.sr^{-1}$]
$L_{v\ image}$	Luminance of the image from a LED projector near the specular spot [$lm.m^{-2}.sr^{-1}$]
$L_{v\ specular}$	Luminance of the specular spot from a LED [$lm.m^{-2}.sr^{-1}$]
m	Ratio of the refractive index of a fibre's core to its cladding
m	Relative refractive index (usually the ratio of the ratio of the particle's refractive index to the matrix containing it)
n	Refractive index
n_{host}	Refractive index of the host matrix containing a TRIMM microsphere
n_i	Refractive index of component *i*, such as a TRIMM microsphere or a light guide matrix
$n_{particle}$	Refractive index of a TRIMM microsphere
n_{pix}	Number of pixels that specular transmission is focused onto
N	Number of measurement positions along a the side of a LSC
N_{LED}	Number of LED chips in hybrid LSC-LED light extractor
N_{pix}	Number of pixels in a display
p	A power index for the fitted variation of the mean half-cone angular spread, $\overline{\Sigma}$, with the axial particle number, *a*
p	Pressure of an inflated tube [Pa]
$p(\theta_i)$.	Path length inside a LSC for light with an angle of incidence of θ_i [m]

$\boldsymbol{P}$	A chosen point at the intersection of the outer surface of a flat-to-round converter a the sidewall [m]
$P(h)$	The cumulative probability density distribution at impact ratio h
$P_a(x)$	Probability of a ray encountering exactly x microparticles in a light guide with an axial particle number of a
PCT	Patent Cooperation Treaty
PMMA	Poly methyl methacrylate, colloquially called "acrylic plastic" or Perspex®
$P_o(\lambda)$	Spectral power of light immediately inside the entry surface of the clear reference sample [counts.sec^{-1}.nm^{-1}]
$P_s(\lambda)$	Total spectral power scattered from the top, bottom and sides of a sheet [counts.sec^{-1}.nm^{-1}]
$P_T(\lambda)$	Spectral power transmitted by a LSC [counts.sec^{-1}.nm^{-1}]
Q	Heat [J]
$\boldsymbol{Q_1}$, $\boldsymbol{Q_3}$	Auxiliary points at the intersection of the outer surface of a flat-to-round converter with a sidewall, chosen to be on either side of $\boldsymbol{P}$ [m]
$\boldsymbol{Q_2}$	Auxiliary point on the outer surface of a flat-to-round converter with the same z value as $\boldsymbol{P}$ [m]
QD	Quantum Dot
r	Particle radius (e.g. of a TRIMM microsphere)
r	Reflectivity of an end mirror
r_i	Radius of the inner surface of the exit ring of a flat-to-round converter [m]
$r_i(z)$	Radius of transverse curvature of the inner surface of a flat-to-round converter at distance z from the entry face [m]
r_n	Radius of the neutral surface of the exit ring of a flat-to-round converter [m]
r_o	Radius of the outer surface of the exit ring of a flat-to-round converter [m]
$r_o(z)$	Radius of transverse curvature of the outer surface of a flat-to-round converter at distance z from the entry face [m]
r_{side}	Nominal radius of the sidewalls' edges in a flat-to-round converter [m]
R	Fresnel reflectance of a surface
R	Reflectance of an optical system
R_1	Reflectance from a single TRIMM microsphere
$\overline{R}_1$	Mean reflectance from a single TRIMM microsphere
$R_{1\ TE}$	Reflectance coefficient from a TRIMM microsphere for light with transverse electric polarisation
$R_{1\ TM}$	Reflectance coefficient from a TRIMM microsphere for light with transverse magnetic polarisation
R_c	Reflectivity of one surface of the collector
R_{end}	Fresnel reflection loss at the far end surface of the LSC
RI	Refractive Index
$R_{particles}$	Mean total back reflectance from a mixer with a microparticles
R_{TE}	Reflectance coefficient for light with transverse electric polarisation
R_{TM}	Reflectance coefficient for light with transverse magnetic polarisation
s	Circumferential stress of an inflated tube [N.m^{-2}]
$\overline{S}$	Mean scattered fraction of light entering an LSC
$\boldsymbol{S}$	The vector normal to the surface of a flat-to-round converter at point $\boldsymbol{P}$ and having a magnitude equal to the sheet thickness, t [m]
$S(\lambda)$	Scattering spectrum [W.m^{-2}.nm^{-1}]

$S(\lambda)$	Spectral intensity of sunlight of wavelength λ [$W.m^{-2}.nm^{-1}$]
$S(\Psi)$	Spectral intensity of sunlight of wavelength Ψ [$W.m^{-2}.nm^{-1}$]
SCATS	Sunlight Collecting And Transmission System
S_T	Side-loss of an optical system i.e. the fraction of light that is transported laterally for a sufficient distance so that it does not enter the entry port of the detector
t	Thickness of a sheet measured perpendicular to the surface [m]
t	Wall thickness of an inflated tube [m]
T	Transmittance of an optical system
$\bar{T}$	Mean tails transmission for light entering an LSC
$T(\lambda)$	Transmission spectrum a LSC sheet
$T(z)$	Distance between the inner and outer surfaces of a flat-to-round converter in the *y-z* plane at distance *z* from the entry face [m]
$T_{diffuse}$	Hemispheric forward transmittance diffuse transmittance of a skylight or other diffuser sheet
TIR	Total Internal Reflection
TRIMM	Transparent Refractive Index Matched Microparticle
$T_{specular}$	Specular transmittance; for a TRIMM system the fraction of rays completely undeviated scattering
U	Symbol for étendue used by some workers. This thesis uses G [$sr.m^2$]
UTS	University of Technology, Sydney
w	Width of the collector sheet [m]
w_C	Width of clear reference sheet [m]
w_D	Width of a dyed LSC [m]
w_{det}	Width of detector port on integrating sphere [m]
$w_i(z)$	Arc length of the inner surface of a transverse cross section of a flat-to-round converter at distance *z* from the entry face [m]
$w_o(z)$	Arc length of the outer surface of a transverse cross section of a flat-to-round converter at distance *z* from the entry face [m]
W	Work [J]
x	Lateral distance on an LSC measured from the entry surface [m]
x	Number of microparticles encountered by a ray
$\bar{x}$	Mean number of microparticles encountered by a ray over a specified distance
dx	Length interval represented by each measurement [m]
$y(\lambda)$	Standard photopic response of human eye
$y_o(z)$	*y* value of the exterior surface of a flat-to-round converter in the *y-z* plane [m]
z_i	*z* coordinate of the bottom of the exit ring in a flat-to-round converter [m]
z_o	*z* coordinate of a sidewall at the exit ring in a flat-to-round converter [m]

Greek Symbols

α Linear particle density i.e. the number of particles per metre intercepted by a straight line drawn through a TRIMM-doped light guide [m^{-1}]

$\alpha(\lambda)$ Attenuation coefficient at wavelength λ [m^{-1}]

$\alpha_d(\lambda)$ Dye-related attenuation coefficient (including the effects of dye photodegradation, if applicable) [m^{-1}]

$\alpha_g(\theta,\phi, l)$ Attenuation coefficient for losses due to light guide geometry [m^{-1}]

α_m Matrix attenuation coefficient, assumed independent of wavelength [m^{-1}]

γ Exponential loss coefficient averaged over all rays [m^{-1}]

δ Semi-cone angular component of a ray's deviation, relative to the previous direction of the ray [rad]

$\bar{\delta}$ Mean deviation angle of the rays interacting with a single TRIMM microsphere [rad]

$\delta(h)$ General expression for deviation angle of a ray impacting a TRIMM sphere, in terms of the impact ratio *h* [rad]

δ_{geom} Deviation angle at the geometric limit [rad]

δ_{median} Median deviation angle of the probability density distribution of the deviation $f(\delta)$ [rad]

δ_{median} Median deviation angle of the rays interacting with a single TRIMM microsphere [rad]

$\varepsilon(\lambda,L)$ Spectral intensity at the collection edge of an illuminated LSC sheet [$W.m^{-2} nm^{-1}$]

$\varepsilon_o(\lambda)$ Emission power spectrum of fluorescent dye [$W.m^{-2} nm^{-1}$]

η_{abs} Fraction of light incident on an LSC collector stack that is absorbed by the dye molecules

$\eta_{conduit}$ Transport efficiency of an LSC system's optical conduit(s)

$\eta_{coupler}$ Fraction of the light reaching a LSC sheet's collection edge that is coupled into the optical conduit(s)

η_{cover} Fraction of light transmitted by the protective cover

η_{direct} Fraction of light from a light extractor that is directed to usefully illuminate a room

$\eta_e(\lambda)$ Energy-to-energy conversion efficiency of fluorescent dye (average emitted photon energy/incident photon energy)

$\eta_{extract}$ Extraction efficiency of a light extractor

η_{geom} Geometric efficiency of a LSC sheet (i.e. losses due to the sheet not being a perfect rectangular prism)

η_{l-l} Lumens-to-lumens efficiency of a LSC system (output lumens/input lumens)

$\eta_{lum-lum}$ Ratio of the luminous efficacy for a dye molecule of the emitted light to that of the absorbed light. Note that $\eta_{lum-lum}$ can exceed 100%

$\eta_{material}$ Efficiency of a LSC sheet due to material properties including: dye self-absorption, absorption by the matrix, scattering by dye particles, scattering by the matrix and absorption at the sheet's end mirror

η_{quant} Photon-to-photon quantum efficiency (photons out/photons in)

η_{sheet} Fraction of the fluorescently emitted light that reaches a LSC sheet's collection edge

η_{TIR} Fraction of the fluorescent emission is trapped inside a LSC sheet by total internal reflection at the top and side surfaces

θ Altitude angle between ray and normal to collector surface [rad]

θ_{crit} Critical angle [rad]

$\theta_{diffuse}$ Half-width of diffuse radiation form a skylight or other diffuser [rad]

θ_i	Angle of incidence of external light entering a collector sheet [rad]
θ_{sun}	Half-width of specular solar radiation [rad]
κ	Lumens per watt conversion factor (683 lm W^{-1}) [lm W^{-1}]
λ	Wavelength of light [nm]
$\langle\lambda\rangle$	The average wavelength of photons emitted by the dye molecule [nm]
$\Delta\lambda$	Wavelength interval [nm]
Ψ	Wavelength of light incident on a LSC [nm]
μ	Difference of the relative refractive index, m, from 1
τ	Spectrometer integration time [s]
ϕ	Azimuthal angle on x-y plane between ray and positive x-axis (long axis) [rad]
Φ	Angle between the geometric cross section surface and the effective cross section surface [rad]
Φ	Inclination of the end surface of a light guide [rad]
Φ	Misalignment angle between two components [rad]
Φ	Radiant flux of a source [W]
χ	Critical angle at the collector-air interface (chapter 7 only – the rest of the thesis uses θ_{crit}) [rad]
$\bar{\Sigma}$	Mean half-cone angular spread of light in the cross-sectional plane of a light guide [rad]
Ω	Emission solid angle of a source [sr]
Ω	Solid angle [sr]
Ω	Solid angle of a light field at a given point [sr]
$\mathit{\Omega}$	Solid angle subtended by a source [sr]
$\mathbf{\Omega}$	Vector of magnitude $\mathit{\Omega}$ in the central direction of a light field that has a solid angle of $\mathit{\Omega}$ [sr]
Ω_{escape}	Solid angle of the escape cone [sr]
$\Omega_{extractor}$	Solid angle subtended by the LSC component of light from hybrid LSC-LED light extractor [sr]
Ω_{LED}	Solid angle subtended by light from an LED [sr]
Ω_{max}	Maximum possible solid angle of light confined in the system at a specified cross section [sr]
$\Omega_{max\ mer}$	Maximum solid angle of meridional light trapped inside an optical fibre [sr]
$\Omega_{max\ rect}$	Maximum solid angle of light trapped inside a rectangular light guide [sr]
$\Omega_{max\ sheet}$	Maximum solid angle of light trapped inside a sheet [sr]

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Abstract

The difficulty of directing daylight deep into the heart of buildings means that much artificial lighting is required during the day, which substantially increases energy costs for lighting and air conditioning. This thesis explores the feasibility of daylighting with luminescent solar collectors.

An LSC is a stack of thin sheets of polymer doped with fluorescent dyes. Sunlight entering the sheets is absorbed and emitted isotropically at longer wavelengths. 75% of this emission is trapped by total internal reflection and propagates towards the sheets' edges. A special coupler channels some of this light into a flexible optical fibre that guides it to a remote luminaire. High quality white light with zero excess heat is produced by appropriate dye use. LSC's collect both diffuse and specular sunlight, so their luminous output is only weakly affected by light clouds.

The best previous LSC's for daylighting gave an outdoor-to-indoor lumens-to-lumens efficiency of only 0.2%. This project achieved an efficiency of 5%.

The basic tool for optical design was étendue analysis. Key results are: i) the system's cross sectional area must not decrease along the optical path, ii) the collector sheets need a high aspect ratio, and iii) an often neglected requirement for a solid optical system with no air gaps. Other optical design problems solved include high-efficiency flat-collector-sheet to cylindrical-optical-fibre couplers and high-efficiency light extractors (which boost output by approximately 50%).

Major advances in mechanical design resulted in several new practical solutions including: strong, enduring optical joints; mass produced collector-sheet to optical-fibre couplers using injection moulding with demonstrated efficiencies of 96%; affordable flexible light guides; high-performance cover materials; roof and façade mounting; and reduced mass.

Required system performance is impossible without high quality LSC sheets. Maximising fluorescence yield involves detailed understanding of the roles of: dye quantum efficiency, Stokes shift, long wavelength absorption "tails", dye dispersion, light transport inside a sheet and long term sheet stability. A substantial improvement in the performance of collector sheets was achieved.

Solutions to all the key problems for daylighting with practical LSC systems have been demonstrated using outdoor mounted collectors channeling light to indoor spaces, with one key exception: the increase in absorption tails over the long term. Techniques were developed for measuring this weak tails absorption, which significantly reduces light output from the required long collector sheets. Suggestions are made as to its cause, and possible methods of its reduction.