Transmission of LED-light through optical fibers for optical tissue diagnostics

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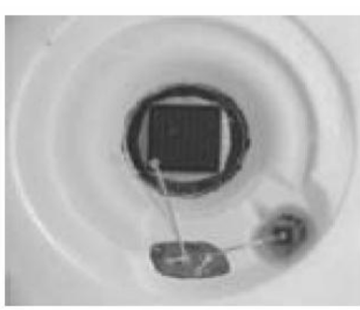
ABSTRACT:

Background:
High brightness light emitting diodes (LEDs) have become available that appear suitable to replace light sources currently used for illumination through thin light guides, e.g. in endoscopy. We investigated the essential characteristics of a series of commercial single LEDs relevant for direct coupling to a single optical multimode fiber.
Methods:
LED fiber coupling efficiency was assessed experimentally and theoretically by using a ray tracing software.
Results:
Surface emitting LEDs proved suitable to be coupled directly into plastic optical fibers (POFs). We have successfully applied a 1 mm core POF-fiber (outer diameter 1.01 mm) in contact with a OSTAR LED (Osram Opto Semiconductors, Regensburg, Germany) to achieve a coupling efficiency of 10-20%, which gave 42 mW, 23.7 mW and 27 mW for blue, green and red LED respectively.
Ray tracing simulation revealed a considerable part of photons travelling “out of axis” in spirals along the core-clad interface (non-meridional beams). They account for approximately 30% of the transmitted power.

Keywords: LED-fiber coupling, high brightness LED, plastic optical fiber, light source, endoscopy

1. INTRODUCTION:

Optical tissue diagnostics requires illumination or excitation with broadband or narrowband light, prefer-ably directed to the tissue surface by optical fibers. Lasers or incandescent lamps are mostly used as light sources for this purpose but are either expensive or inefficient. LEDs offer a potential alternative. Coupling of LED light to optical fibers is, however, a challenge and requires high intensity LED-chips with special features.
Here we consider only direct fiber coupling to front-surface emitting LED-chips. The major precondition for efficient coupling in this case is to achieve a minimal gap between chip-surface and fiber-core. This means that the surface electrode must be bonded at one of the edges and only a thin layer of silicone is allowed on top of the chip. This is available to a good approximation with chips from OSRAM company, OSTAR and Golden Dragon II. Fig. 1 shows microscopic images of a red “Golden Dragon II”.



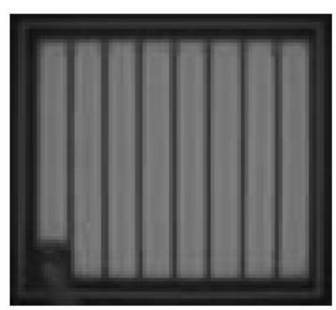


Fig. 1: Golden Dragon II LED. Left: Chip with bonding in its housing, right: close-up view of the irradiating surface and the bonding wire in the lower left corner. Emitting surface is 0.94 mm x 0.94 mm.

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2. MATERIALS AND METHODS:

LED-chips used were OSTAR Projection LE ATB A2A and Golden Dragon LB, LV, LT W5SG (OSRAM Opto Semiconductors, Regensburg, Germany).
Ray tracing simulations were performed using ASAP software (Breault RO, Tucson, AZ).
Light power emitted from the LEDs was measured with a calibrated integrating sphere, light power emitted from fibers with a calibrated power meter (fieldmaster, Coherent, Santa Clara, CA).
Radiation profiles were measured in near field (approx. 2 mm) from the LED-chip surface by mounting the LED on a goniometer and grabbing the light with a quartz fiber.
Fibers used for coupling were either a plastic optical fiber (POF) with 1 mm core and NA = 0.46 or a 1.5 mm core fused silica fiber with NA = 0.40.

3. RESULTS AND DISCUSSION:

The radiation profiles of some front surface emitting LEDs have been measured and determined to be near Lambertian. Fig. 2 shows the emission profiles of Golden Dragon and OSTAR LEDs, which have been chosen for further experiments due to favourable geometric conditions (see above).

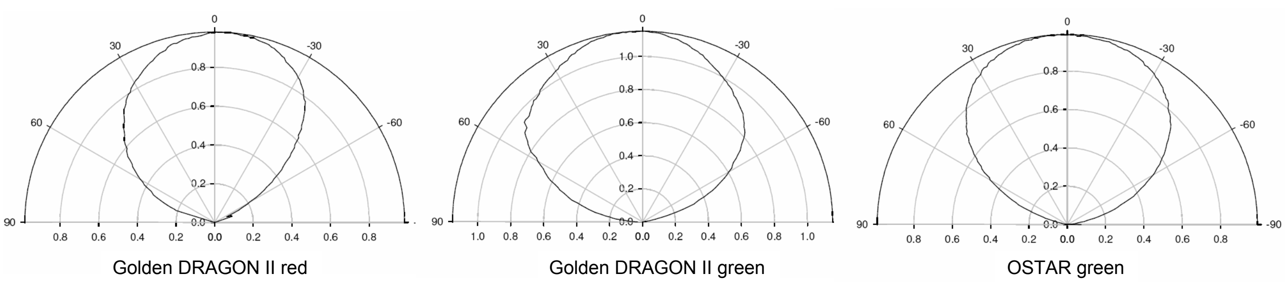

Fig. 2: Near field angle dependent emission profiles of Golden DRAGON II and OSTAR LED chips.

The proportion of light emitted by a Lambertian source within an angle of φ from the normal is calculated as follows: A Lambertian source appears equally bright from whichever angle observed. As the projected area of the source varies with the cosine of the observation angle, this means that the emitted intensity $I_e(\delta)$ and power $d\Phi_e$ per unit solid angle $d\Omega$ are also reduced with the cosine:

$$I_e(\delta) = I_e(\delta = 0) \cdot \cos\delta = I_{e0} \cos\delta \qquad (1)$$

With

$$d\Phi_e = I_e(\delta) d\Omega \qquad (2)$$

and

$$d\Omega = 2\pi \sin\delta \cdot d\delta \qquad (3)$$

we obtain

$$\Phi_e = I_{e0} \cdot 2\pi \int_0^{\varphi} \sin\delta \cos\delta d\delta = I_{e0} \pi \sin^2 \varphi \qquad (4)$$

Thus, the proportion of light emitted by a Lambertian source within an angle of φ is proportional to $\sin^2\varphi$. If the Lambertian source were a point source and placed in almost contact in the center of a fiber with a given Numerical Aperture NA=sin φ, a proportion of NA^2 emitted from that source will be accepted by the fiber. In case of the POF used with NA = 0.46, this means that a maximum of 21.2% minus the loss due to reflection at the fiber surfaces, that is ca. 20% can be transmitted through the fiber. The exact value has been determined by ray tracing simulations with a geometry schematically shown in fig. 3 to be 19.52%.

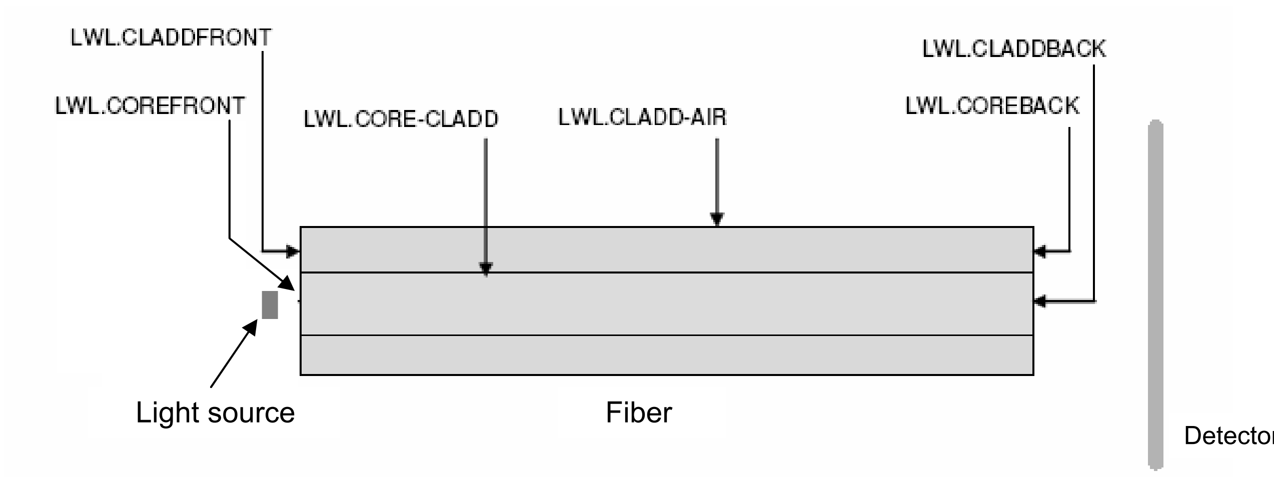

Fig. 3: Schematic, illustrating the ray tracing simulation of the fiber coupling efficiency of a point source.

However, an LED cannot be considered a point source, but has an emitting surface area approximately equal to the bare cut light guiding fiber. Then, beams enter the fiber, that will not intersect with the fiber axis (non-meridional beams, illustration fig. 4). Such beams can travel a helical curve through the fiber without being lost, although the entrance angle of beams into the front surface of the fiber exceeds the acceptance angle. The ray tracing calculation with a square Lambertian LED-emitter with 0.94 mm x 0.94 mm surface into a 1 mm core diameter POF gave an overall efficiency of 25.7%. Losses of 8.9% are caused by the mismatch of fiber front surface area with respect to the LED-area.

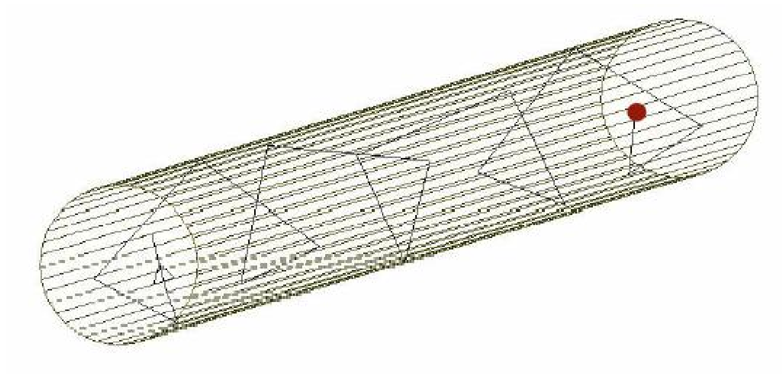

Fig. 4: Illustration of the travel of a non-meridional beam through a fiber core.

The calculated efficiency of almost 26% could largely be confirmed experimentally (>20% OSTAR green and blue, fig. 5). Comparing the efficiencies of a point source and the extended sources with its mismatch losses, about 30% of the transmitted power in the extended source case is transmitted as non-meridional beams. This part of the transmitted power, however, cannot be transmitted further through a fiber bundle connected to this first POF. A ray tracing calculation of this situation (compare fig. 6) shows almost no difference of the overall transmittable power whether the light source was defined as a point source or as the 0.94 mm square (14.69% efficiency (point source) versus 14.46% efficiency (extended source)). The efficiency in the latter case could, however, be higher by about 9% (resulting in 15.7%), if the areas of LED and fiber matched exactly.

The design of LED-based light sources for endoscopic applications has to consider the effects produced by non-meridional beams. It may also have measurable influence on spectroscopic fiber optic equipment, when it is sensitive to the numerical aperture, as is the case for fluorescence detection using a single optical fiber for excitation and detection [1].

				Quartz-fiber $\varnothing_K$=1.5mm		POF $\varnothing_K$=1.0mm	
	LED	λ [nm]	Φ_E [mW]	Φ_D [mW]	η_K [%]	Φ_D [mW]	η_K [%]
blue	C11A1-HB	463	99.75	25.40	25.46	17.00	17.04
	Golden Dragon	472	180.00	16.60	9.22	9.00	5.00
	Golden Dragon II	458	260.00	43.40	16.69	31.50	12.12
	Z-Power	452	712.00	13.00	1.83	14.00	1.97
	Ostar	462	208.00	56.00	26.92	42.00	20.19
green	Golden Dragon	520	93.00	9.40	10.11	6.20	6.67
	Golden Dragon II	525	123.00	20.20	16.42	15.00	12.20
	Z-Power	532	365.00	32.50	8.90	5.20	1.42
	Ostar	515	118.00	27.00	22.88	23.70	20.08
	Prolight 5W	522	340.00	7.80	9.18	6.20	7.29
red	C11A1-HR	632	16.72	6.60	39.47	4.75	28.41
	Golden Dragon II	617	267.00	29.60	11.09	22.00	8.24
	Z-Power	632	692.00	29.80	4.31	17.80	2.57
	Ostar	628	252.00	36.80	14.60	27.00	10.71

Fig. 5: Experimental results. Φ_E: total emitted power (integrating sphere), Φ_D: power transmitted through fiber (power meter), ηK: efficiency Φ_D/Φ_E in %.

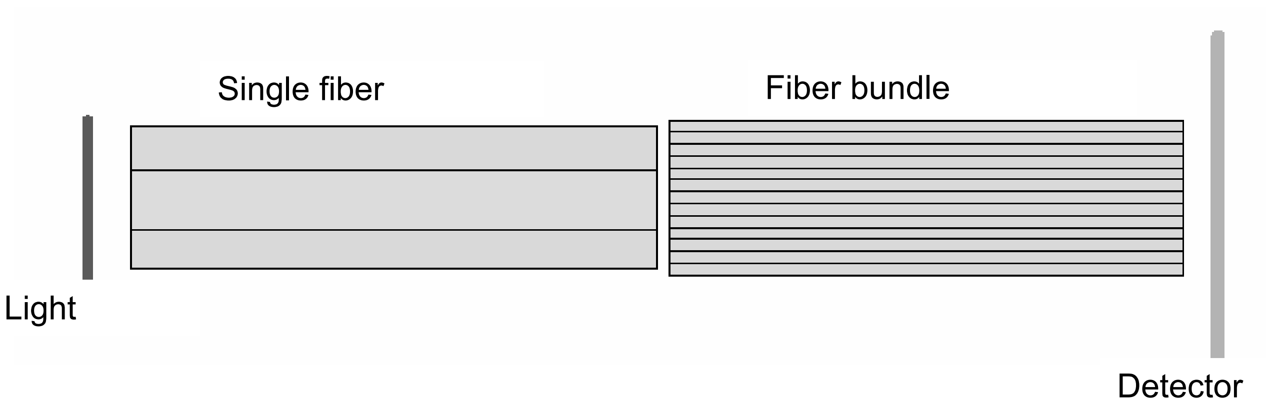

Fig. 6: Schematic for calculating the efficiency of LED-light transmission through fiber optic bundles.

The highest overall transmitted power achieved through a single POF was 42 mW, 23.7 mW and 27 mW (OSTAR blue, green, red). Although largely similar to OSTAR, Golden Dragon LEDs proved to be less efficient in direct fiber coupling (fig. 5). The most probable reason is the significantly thicker silicone layer on top of these chips.
The OSTAR Projection LED combines a blue, two green and a red LED in closely packed 2x2 square arrangement. The driving currents can be individually set. By placing four POFs in a square arrangement, light of all three colors could be

transmitted in individual fibers to the output port of a prototype LED-light source, thereby enabling one to accurately reach the white point of the CIE-diagram. However, for combining individual monochrome LEDs, fiber coupling using an appropriate set of dichroic mirrors and imaging or light guiding optics, a higher overall efficiency can be obtained.
A possible application for coupling LED light into small diameter light guides is endoscopic illumination or fluorescence excitation. The active area of the illumination bundle of a typical endoscope is 1-2 mm². We have measured the output power of white light at the distal tip of a rigid cystoscope required for sufficient illumination in a bladder phantom in 3 cm distance to be 40 mW. This was sufficient to expose an endoscopic 1-chip CCD-camera to provide images in realtime (exposue 1/60 s). When we compare this requirement with the efficiencies of fiber coupling, knowing that new white light LEDs emit up to 1 W from 1 mm², low cost and efficient LED illumination for endoscopic medical application should be feasible.

4. CONCLUSION:

High brightness LEDs, although being lambertian emitters, provide enough efficiency for direct fiber coupling to appear suitable light sources for fiber based illumination. The considerable contribution of non-meridional beams emitted from a single fiber coupled directly to an LED-chip has to be considered, when calculating overall efficiencies of such light sources.

5. ACKNOWLEDGEMENTS:

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