APPLICATION NOTE

FIBER COUPLING EFFICIENCY CALCULATION

Submitted to :

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1. INTRODUCTION

This document on fiber coupling efficiency use a geometrical approach to approximate maximal coupling power that can be coupled into a fiber. Since the development is relatively straightforward, there is no long mathematical demonstration or detailed physical explanations.

The formulas given is this document can be used to have a good approximate of fiber coupling efficiency. Theses are not exact because they are base only on geometrical considerations, but in most case, it gives a good idea of the power that can be coupled into a fiber.

2. GENERAL EQUATION

The efficiency of direct coupling of a source into an optical fiber is affected by three different factors. Theses factors are : geometrical losses, Fresnel losses and angular losses.

$$\eta=\left(\frac{P_{input}}{P_{source}}\right)=\eta_{geo}\times\eta_{Fresnel}\times\eta_{ang}$$

where :
- η = Fiber coupling efficiency
- P_{input} = Pow er couplet into the fiber
- P_{source} = Pow er emitted by the source
- η_{geo} = Geometrical losses factor for coupling efficiency
- $\eta_{Fresnel}$ = Fresnel losses factor for coupling efficiency
- η_{ang} = Angular losses factor for coupling efficiency

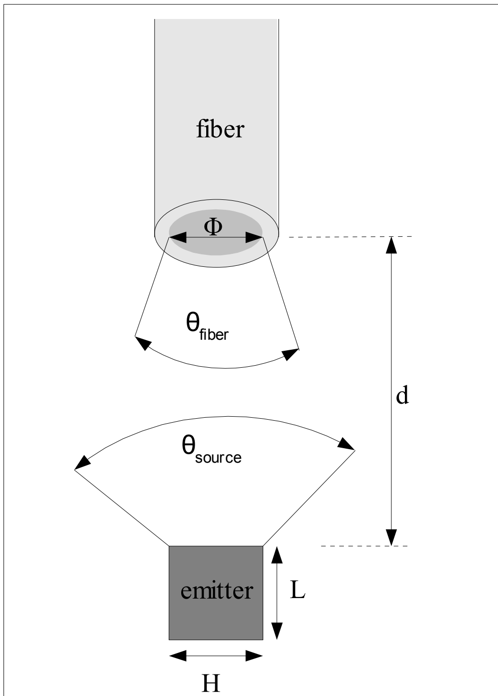

Fig 1. a) Schematic of butt coupling

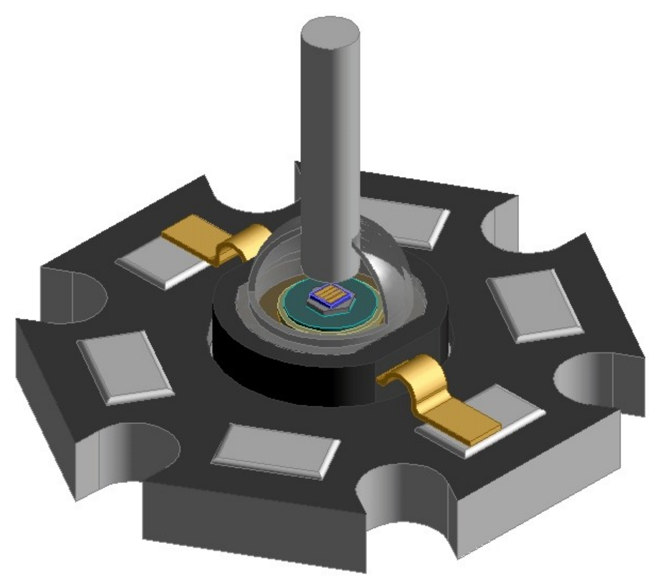

Fig 1. b) Luxeon III pigtailed LED

3. GEOMETRICAL LOSSES

The light emmited by a source of area (A_{source}) can be butt-coupled into an optical fiber which is larger the the source area. The light incident outside the core area will not be guided by the fiber. There is three possible configuration for emitter and fiber area :

- First, if the source dimensions (H, L) are smaller than fiber core diameter, all the light will be coupled into the fiber.

IF : (Φ > H) & (Φ > L),
THEN : $\eta_{geo} = 1$

- Second, if the source is larger than fiber core area , the geometrical factor for coupling efficiency is given by the ratio of light captured by the fiber.

IF : (Φ < H) & (Φ < L),
THEN : $\eta_{geo} = \left(\dfrac{\pi \phi^2}{4\mathrm{H} \times L} \right)$ <u>where</u> : Φ is fiber core diameter, H is emitter height and L is emitter length.

- Third, if fiber core diameter is larger than one side of the source, but is smaller than second side. That can happened with laser diodes that are typically 1 µm heigth by some hundred microns long.

IF : (Φ < H) & (Φ > L),
THEN : $\eta_{geo} = \left(\dfrac{\phi}{L} \right)$ <u>where</u> : Φ is fiber core diameter and L is emitter length.

4. FRESNEL LOSSES

The light incident on an interface between two dielectric media of different refractive index is partially transmitted and partially reflected (assuming linear, homogeneous and isotropic media). The proportion of light reflected and transmitted depend on light polarisation and incidence angle and can be calculated from Fresnel equations based on electromagnetic theory. In this document, we do not present the development leading to the result we need, for a complete theoretical treatment, refer to references [1] or [2].

The power reflectance at normal incidence is then given by :

$$R = \frac{(n_{fiber} - 1)^2}{(n_{fiber} + 1)^2}$$

Fresnel factor for coupling efficiency is approximatly equal to :

$$\eta_{Fresnel} = 1 - R$$

NOTE : In butt coupling, the fiber is fixed directly on the emitter with a matching index gel and glue, so Fresnel losses at the fiber input end can be neglected.

5. ANGULAR LOSSES

The following explanations are quite short ,but we hopes there is enough information to be well understood.

5.1. SOURCE ANGULAR DISTRIBUTION

First we should assume a source with cosinusoidal power angular intensity distribution :

$$I(\theta)=I_0(\cos\theta)^m$$

Most of the time manufacturer of laser diodes, or LED gives the divergence angle at full width half maximum (θ_{FWHM}). In order to link this data to previous formula, we can find value of cosinus exponent by :

$$m=\frac{\log(0.5)}{\log\left(\cos\left(\frac{\theta_{FWHM}}{2}\right)\right)}$$

* In the case of a Lambertian source, the value of m is 1 (θ_{FWHM} = 120°).

5.2. OPTICAL FIBER ACCEPTANCE ANGLE

Optical fibers can guide light only if the angle is smaller than the critical angle of the fiber (θ_{fiber}).
The acceptance angle is typically related to fiber numerical aperture (NA) :

$$NA=\sin(\theta_{fiber}) \quad \text{-->} \quad \theta_{fiber}=\arcsin(NA)$$

5.3. ANGULAR COUPLING EFFICIENCY FACTOR

Now that the source angular distribution and the fiber acceptance angle are well defined, it can be demonstrated that the angular coupling efficiency factor is :

$$\eta_{ang}=1-(\cos\theta_{fiber})^{m+1}$$

In most cases of laser diode coupling to fiber, the emitter is not circularly symmetric and have different divergence angle depending of azimut angle.

For example, side emitting laser diodes : typically, they have a two main directions. One direction with smaller dimension and higher divergence called fast axis, and another direction with larger dimension and lower divergence called slow axis.

In that case, we can get a good approximate for coupling efficiency by calculating efficiency in both axis separatly, by supposing a revolution symmetry for both axis separatly, and multiply the square root of the computed efficiency for each axis.

$$\eta = \sqrt{\eta_{slow\,axis}} \times \sqrt{\eta_{fast\,axis}}$$

In fact, we should integrate the contribution of each axis, but this approximation is close in most cases.

6. SUMMARY

A simple geometric expression has been developped to get an approximation of butt-coupling efficiency of a laser diode or LED emitter into an optical fiber.

Depending on emitter geometry and divergence symetry, different factor are used for geometrical and angular efficiency factors, so we cannot summarize all cases in only one general expression for coupling efficiency. We have to compute the 3 factors separatly and multiply to get the total coupling efficiency.

$$\eta = \left(\frac{P_{input}}{P_{source}} \right) = \eta_{geo} \times \eta_{Fresnel} \times \eta_{ang}$$

7. EXAMPLES

Coupling efficiency have been calculated for different emitter and fiber type combination.

The results are summarized in the following table and graph.

Emitter			Fiber		η
Type	***Dimension***	***θ_{FWHM}***	***Φ_{CORE}***	***NA***	
LED Luxeon III	1 x 1 mm	120°	100 µm	0.22	0.03 %
			200 µm	0.22	0.12 %
			200 µm	0.39	0.37 %
			1.0 mm	0.50	15.2 %
Laser diode	1 x 100 µm	30° x 10°	50 µm	0.22	29.4 %
			62.5 µm	0.22	36.8 %
			100 µm	0.22	58.6 %

Some theoretical values for fiber butt-coupling efficiency

8. REFERENCES

[1]. David K. Cheng, *Field and Wave Electromagnetics (2nd edition)*, Prentice Hall (1989).

[2]. B. Saleh and M.C. Teich, *Fundamental of photonics*, Wiley-Interscience (1991).