Master in Photonics

MASTER THESIS WORK

IR LIGHT SOURCE BASED ON LED FOR ENDOSCOPY APPLICATION

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IR light source based on LED for endoscopy applications

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Abstract. A specific endoscopy technology uses an InfraRed (IR) light to achieve specific imaging of the vascular system. This IR light is obtained by an IR laser source. The aim of this study is to find a new IR illumination built with LEDs to substitute the existing IR source. LEDs may contribute in the endoscopy application with their advantage: LEDs cost is lower than lasers, LEDs have a longer lifetime, LEDs are available in a wide range of wavelengths, and LEDs have a narrower bandwidth in comparison to halogen or incandescent lamps. Fiber pig tailing is explored as it is the less complex and highly scalable. The research includes a depth analytical study and laboratory measurements of the IR LED fiber pig tailing approach.

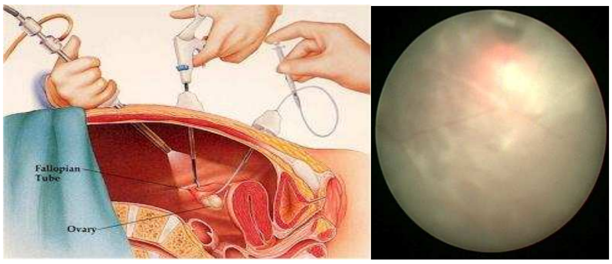
Keywords: Illumination, LED, optical fiber, endoscopy

1.Introduction

1.1*Motivation.*

Endoscopy has been a revolutionary diagnostic and therapeutic tool used in medicine to visualize intern organs developed in the early 19th century. Endoscopy fundamentally involves a device illuminated by a light source, and a camera attached to the endoscope through which internal body cavities can be visualized. The enormous success of endoscopy led 100 years ago to the first laparoscopic surgery in humans [1], which is the natural evolution of open surgery to an endoscopy mediated surgery that avoids major incisions on the patient by incorporating additional tools to a fundamental endoscope. This approach dramatically reduced the post operational time for recovery and significantly reduced number of complications of patients which boosted the field of research devoted to the development of minimally invasive surgery.

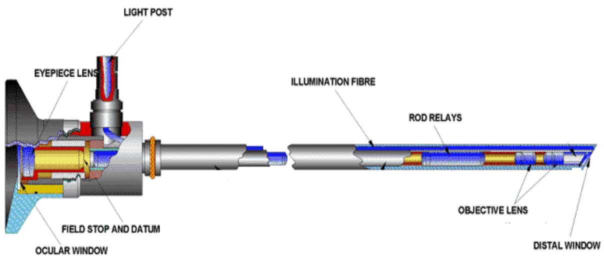
In this line, Transmural Biotech has developed a new device named endoVascularVision (endoVV) to be connected to an endoscope or laparoscope that provides assisted vision to surgeons and other endoscopists, which will increase the repeatability and safety of many endoscopic procedures. Particularly, endoVV is currently going through pre-clinical and clinical studies focused in two types of laparoscopic procedures related to fetal and gynecological complications in collaboration with opinion leaders of the field from Hospital Clínic de Barcelona and Katholiken University of Leuven.

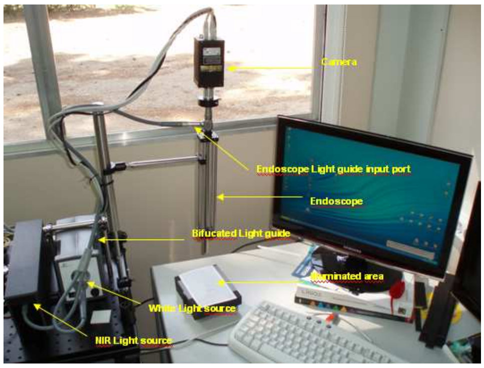


(a) (b)

Figure 1. (*a) Illustration of laparoscopic procedure and (b) typical laparoscopic image. The laparoscope, is introduced in the abdominal cavity trough several incisions. A special CCD camera is adapted to the laparoscope to obtain a high resolution interns organs images.*

EndoVV will provide to the next generations of endoscopes the ability to visualize blood vessels in real-time which will be an invaluable tool for all types of surgeons and endoscopists. For this, endoVV critically requires at least two light sources: the standard white visible spectrum light source and an InfraRed (IR) light source. This work will be primarily centered in the development of a light source based on LED to provide IR illumination to endoVV.





(a) (b)

Figure 2. *Endoscopic components. (a) conventional medical endoscopic. (b) Endoscopic prototype with endoVV components*

1.2State of the art

Nowadays, Xenon lamps are used in regular endoscopic technologies as the white light source and possess a long tail in the IR spectra that unfortunately does not provide enough light within a limited bandwidth for our application. Discharge lamps are lightly more efficiency than incandescent lamps and the appearance of the color has been reported to be more comfortable [1][2]. Discharge lamps are based in the luminescence phenomenon. EndoVV requires two light sources: a white light source and a specific narrow band IR light source.

IR light is now obtained by means of an IR solid state laser in the research system; however, recent advances in the LED technology, particularly related to optical power and availability of wavelengths, and other optical component might perform at sufficient level to change our illumination system from laser based to LED. LEDs provide some interesting advantages from our prospective: LEDs are much more cost effective, work with lower power levels compared to laser systems and the overall optical setup can be simplified and reduced in some cases. Additionally, incoherent light sources (like LEDs) are in general preferred in wide field illumination systems because they do not produce images with coherent interference (like fringes or speckles) as can occur with lasers.

Although all these advantages, it is true that LEDs do not provide the same spectral purity (or narrow bandwidth) as lasers but it is sufficiently good for our application (30-50nm FWHM). Furthermore, they do concentrate enough spectral power density within a limited bandwidth when compared with other incoherent light sources like discharge lamps.

However, one of the major drawbacks of coupling LED light into a fiber compared with laser is the huge difficulty of focusing incoherent light (which is physically impossible) [3].

In order to overcome this major limitation and find an optimal LED based scheme to couple enough light at a given wavelength at the same level than the current laser based scheme, many LED based illumination schemes are reviewed below. From the current state of the art we already find three strategies to couple LED light to an optical fiber:

1.*IR LED fiber pig tailing)*: (Figure 1c) LED is coupled to an optical fiber, and then multiple fibers coupled could be assembled in a fiber bundle.

2.*Multiple IR LED coupling with lenses:* (Figure 1b) the power of an array of LEDs is coupled to the endoscope's fiber bundle through several lenses. A small focal lens captures the LED light emission, collimates and drives it to a bigger diameter and longer focal distance lens. The second lens' role is to focus and concentrate the whole power of the array in the input end of the endoscope's fiber bundle.

3.<u>*Direct LED coupling to fiber bundle input port*</u>: (Figure 1a) A direct LED coupling to the endoscope's fiber bundle. This approach consists of placing a high intensity LED in the light source end of the fiber bundle.

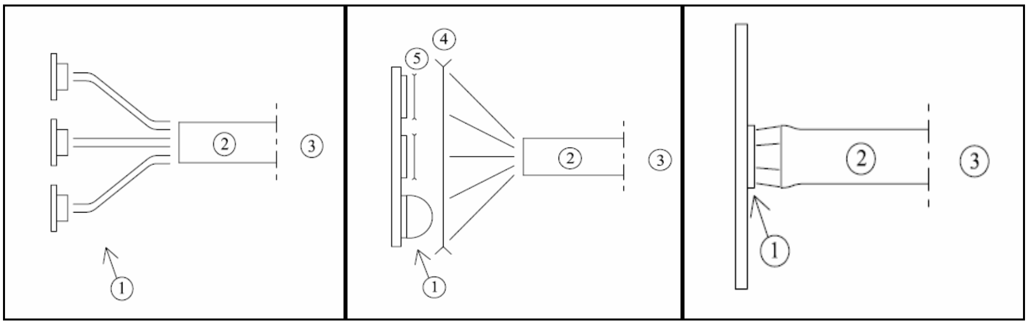


Figure 3. *Scheme of the three proposals: a) IR LED fiber pig tailing. Several optical fibers (1) are the connection between LEDs and the fiber bundle (2) to the endoscope input port (4).b) multiple IR LED coupling with lenses; Several lenses (5) collimate the LED light emission. Lenses could be integrated (1) or not. Lights LEDs emission is driven to a Fresnel Lens (4) where the light is focused in the fiber bundle (2) c) direct LED coupling to fiber bundle input port, LED(1) is directly illuminating the fiber bundle (2). Fiber bundle is the responsible to drive light until the endoscope (3)*

In summary, an illumination system based on laser technology needs a complex mechanism to operate: a thermal management system, a method to suppress optical interferences from coherent light; therefore LED based illumination systems cost are incomparable with their laser counterparts which makes worthy to explore the potential use of an LED as light source for an illumination system in endoscopy.

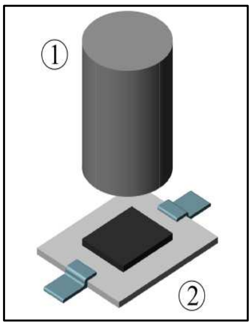


Figure 4.*Fiber Coupled IR LED. Fiber(1) is placed in the maximum LED emission point (2). Not to scale*

The IR LED fiber pig tailing approach was chosen for this research. The multiple IR LED coupling with lenses approach presented a mechanical assembly challenge. It also needed more components making the numerical analysis more complex. The direct LED coupling to fiber bundle input port approach was discarded because a preliminary research showed that there were no commercial LED available in the market that would satisfy the objective. On the other hand the IR LED fiber pig tailing approach was mechanical and optically simpler. It is also a common used technique in the communication industry. For these reasons, we decided to explore the ability of such strategy for obtaining a good LED coupling to a commercial rigid endoscope system.

1.3*Specific objectives*

The main objective of this work is to determine the maximum optical power within a limited bandwidth of IR light that can be coupled within a single optical fiber by LED pig tailing. For this, different LEDs and optical fibers will be pigtailed with epoxy and the optimal arrangement will be established.

Secondary objective will evaluate the feasibility of achieving sufficient illumination for clinical applications (180mW at the input port of the endoscope's light guide or 1,5W at the light source output) by using multiple pigtailed LEDs.

2.Methods

The methodology described in this works involves a numerical analysis in combination to experimental analysis.

2.1*Numerical Analysis*

The numerical analysis is used to estimate the influence of the different characteristics of the LED and the optical fiber to the coupling efficiency and the optical losses. This numerical model [4][5] will be used as a tool to choose the fiber and LED optimal combination to implement in the laboratory.
In the numerical analysis, the coupling LED and fiber efficiency is resolved. Three main coupling losses have to be considered: 1) Difference in geometry of LED and fiber, 2)Difference in numeric aperture between the LED emission and the fiber, 3)Reflections due to the dielectric medium change from air to the fiber. The study comprises a numerical analysis of the optical system and experimentation in the laboratory to check the correct numerical modeling.
The coupling efficiency is defined as the ratio of power emitted (P_{source}) by the power obtained after the coupling (P_{output}). The efficiency depends on three factors:

$$\eta = \frac{P_{output}}{P_{source}} = \eta_{geo}\ x\ \eta_{Fresnel}\ x\ \eta_{ang} \tag{1}$$

where η are the efficiency corresponding to geometry, Fresnel phenomenon or angular emission and P_{output} is the power measured at the output of the optical system formed by the LED coupled to the optical fiber and P_{source} is the LED emitted power taken from the specs. The total efficiency is the product of the all the efficiencies which could influence in the transmission of light through the optical fiber.

2.1.2Geometrical Efficiency

Surface emitting LEDs are usually built with a square geometry, and fiber has a circular cross section, therefore depending on the dimensions of the LED and fiber losses can be produced. To calculate it, three cases have to be considered:
1. The fiber is large enough to capture all light emitted by the LED. This case is when the core diameter of the fiber is larger than the LED diagonal, then the total efficiency of the fiber and LED coupling is 100%, loss is 0.
2.The fiber is not large enough to capture all the light emitted by the LED. This case is when the core diameter of the fiber (d) is smaller than the side of the LED emitting area (L), and then only a fraction of the light emitted by the LED will be captured by the fiber. Since surface emitting LED are assumed and the emission of the emitting area is considered homogeneous, the amount of light captured by the fiber can be assumed as a direct relationship between the LED emitting area and the fiber input area. The efficiency can be calculated as follows[4]:
3.

$$\eta_{geo} = \frac{P_{out}}{P_{in}} = \frac{P_{em} \cdot A_f}{P_{em} \cdot A_L} = \frac{\pi d^2}{4L^2} \tag{2}$$

where P_{em} is the power emmited, A_f is the optical fiber cross section area and A_L is the surface of the LED.
4.The fiber diameter is of a similar dimension of the LED cross section. This case is when the fiber diameter is smaller than the LED diagonal and larger than the LED side. This case has not been considered as it is difficult to calculate and it will not be implemented.

LED emitting area and optical fiber input face are not in contact, they are some distance apart. Hence this fact has to be considered in the geometrical efficiency calculus, in the size of the LED emitting area side (L) used. This size used to compares the LED and optical fiber geometry is the effective size as they will be at certain distance, a bigger effective light emission effective side is created. The effective size of the LED emission through the media (epoxy and air), is calculated as an image formed by the divergence of the exit light beam LED emitting. The distance between the

LED and the fiber input is difficult to measure and is also difficult to model due to lack of specification in the LED manufacture's datasheets. An estimation was made measuring the LEDs datasheet drawings. The distance supposed between the LED chip and optical fiber core is 0,75mm.

2.1.2Fresnel Efficiency.

Fresnel Losses are also known as reflection losses, then, Fresnel efficiency is referent to the transmitted light. Reflection losses are caused by a step change in the refractive index that occurs at the fiber interface. The step change in refractive index is caused by the end of the fiber being separated from the LED emitting are by a small gap. This small gap is usually an air filled gap. Fresnel losses are calculated through:

$$\eta_{Fresnel} = \frac{(n_f - n_m)^2}{(n_f + n_m)^2} \tag{3}$$

Where n_f is the refraction index of the fiber and n_m is the refraction index of the medium where light is traveling. Usually these losses are approximately a 4%, and they could be cancelled if the air gap is filled by an epoxy resin. Epoxy refractive index is similar to the fiber refractive index (epoxy refractive index is 1.5, fiber refractive index 1,47).

2.1.3Angular Efficiency

By assuming ray theory ,[6] the light from the LED which may be coupled inside the optical fiber, is confined to the beams which satisfy the condition: $\theta_a \geq \theta_{LED}$ (4) where θ_{LED} is the LED emitting cone angle and θ_a is the optical fiber acceptance cone angle [3].

The acceptance cone angle θ_a is related to the fiber Numerical Aperture by: $NA = sen(\theta_a)$(5) where NA represents the Numerical Aperture, the collector light power of the system.

For maximum coupling efficiency the LED emission angle should not exceed the fiber acceptance angle θ_a. The LED surface emission angle is wider than θ_c. The pattern intensity ($I_{\theta c}$) of the LED surface emission is Lambertian. The LED emission is described as:

$$I_{\theta c} = I_0 cos^s(\theta_{LED}) \tag{6}$$

where:

$$s = \frac{\log(0{,}5)}{\log(\cos(FWHM)} \tag{7}$$

Therefore, the light emitted by LEDs and captured by the optical fiber is defined with the shape parameter s, and the numerical aperture as:

$$\eta_{ang} = \frac{I_{in}}{I_{tot}} = \frac{\int_{\theta_a=0}^{\theta_a=arsin(NA)} cos^s(\theta_a)}{\int_{\theta_a=0}^{\theta_a=90} cos^s(\theta_a)} \tag{8}$$

2.2Experimental Analysis

The numerical study includes the estimation of 50 different combinations of LED and fiber (5 types of LEDs: 3 single-LEDs and 2 LEDs arrays and 10 optical fibers). LED cross sections are between 1 mm^2 to 4,2 mm^2 and their optical powers are between 160 and 720mW.The full width half maximum (FWHM) emission angles are very similar in all the LEDs studied, from 60 to 65 degrees. The optical fibers of the study have different core diameters and numerical aperture (related to the angular acceptance). Their refractive index is very similar in all of them because of the materials used in their fabrication. Optical fibers' core diameters included in the study are from 200 microns to 3000 microns. The numerical apertures have values from 0,22 to 0,50. [7]

These range in fiber and LED characteristics enabled us to validate our numerical analysis and determine the optimal conditions with commercial items.
The method used to prepare the LED fiber coupling is described as follows: 1. LED was soldered on a purpose made (printed circuit board) PCB in order to provide electrical connection to the LED, heat dissipation, ease of handled and a means of mechanical fixing; 2. Optical fiber tips were assembled to an acrylic purpose made ferule to provide a means of mechanical interface to the fiber so it could be easily handled; 3. Optical fiber was polished to a surface finish flatness of 300nm in order to reduce the Fresnel Losses
The LED PCB assembly was held firmly in the optic bench and one of the fiber ends was positioned over the LED emitting area with an XYZ micrometer positioning stage until maximum power was measured at the output of the fiber.

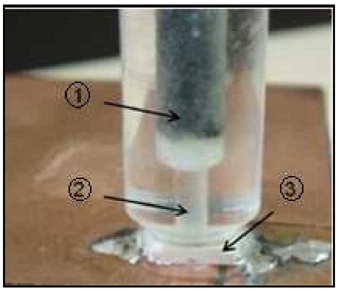


Figure 5.*LED and optical fiber coupling. The jacked of the fiber (1) is stripped and the core (2) is positioned by a micrometer displacement stage over the LED emitting area (3) and bonded with epoxy resin.*

All the measurements were made in a dark room condition. The LED was driven by a laboratory power source; the power supply was set to constant current mode. The LED fiber assembly was securely held on an optic bench. The output end of the fiber was directly coupled to a photometer THORSLABS PM100A using standard optical mechanics from Thorslabs in order to drive light until it. Before starting the experiment the photometer was set to zero to compensate for the ambient background light.

2.3Relationship between Numerical and Experimental Analysis

We use two measurements to evaluate the goodness of our numerical calculations: relative error (RE) and marginal experimental efficiency (η_{marg}). Relative error between experimental measurement and numerical calculation is the standard procedure to assess the deviation in our calculation as follows:

$$RE = {|\eta_{measurement} - \eta_{estimated}|}/{\eta_{measurement}} \tag{9}$$

Marginal experimental efficiency (η_{marg}) accounts for additional experimental effects which have not been considered in our numerical analysis which can be related to fiber diameter by an exponentially decaying function for experiments of LED 3.

$$\eta_{marg} = {\eta_{measured}}/{\eta_{estimated}} \tag{10}$$

3.Results

Three LEDs and two LEDs arrays were numerically combined with 10 optical fibers in order to estimate their efficiencies: geometrical, Fresnel, angular, and finally the total efficiency. The experimental study does not include the 50 possible combinations; only six of them were later measured in the laboratory.
Numerical results obtained are used to choose some combination to investigate in the laboratory. Several other combinations were chosen for their scientific interest in the study although their numerical results have not the highest efficiency.

3.1Numerical Efficiency

The estimated total efficiency for the 50 different combinations has relatively low values as expected, ranging from a 0,08% to a 32,3%.

The product of the estimated total efficiency (η) and the LED emitted power is referred as the total radiant intensity. The estimated total radiant intensity (P) is calculated for the 50 LED and optical fiber combinations are shown in Table 1. The fibers of the study are in rows and in columns we can find the LEDs of the study. The total radiant intensity is expressed in mW units.

	LED 1		ARRAY LED 1		LED 2		ARRAY LED 2		LED 3	
	P (mW)	η (%)	P (mW)	η (%)	P (mW)	η (%)	P (mW)	η (%)	P (mW)	η (%)
FIBER 0,2 mm	0,30	0,19%	0,54	0,08%	0,77	0,21%	1,21	0,08%	1,69	0,28%
FIBER 0,3 mm	0,72	0,45%	1,28	0,20%	1,81	0,50%	2,87	0,20%	2,95	0,50%
FIBER 0,55 mm	1,32	0,83%	2,44	0,38%	3,46	0,96%	5,49	0,38%	5,65	0,94%
FIBER 0,98 mm	9,67	6,05%	17,24	2,96%	24,52	6,81%	38,82	2,70%	40,47	6,74%
FIBER 1mm	10,12	2,82%	18,04	2,82%	25,65	7,12%	40,61	2,82%	41,72	6,95%
FIBER 1,48 mm	21,77	13,6%	38,80	6,06%	55,17	15,3%	87,35	6,07%	89,34	14,9%
FIBER 1,5 mm	17,01	10,6%	30,31	4,74%	43,07	12,0%	68,19	84,7%	70,14	11,7%
FIBER 1,96 mm	38,70	24,2%	68,97	10,8%	98,09	27,2%	155,30	10,8%	158,83	26,5%
FIBER 3mm	51,65	32,3%	157,19	24,6%	113,20	31,4%	353,95	24,6%	188,24	31,4%

Table 1. *Numerical results of the total expected radiant intensity (mW)*

Table 2 show the Total Power expected on 3,5 mm circular section. These values are the product of the Irradiance (power by unit area) and the endoscope fiber bundle section.

	LED 1	ARRAY LED 1	LED 2	ARRAY LED 2	LED 3
FIBER 0,2 mm	98,43	171,86	234,5	386,16	552,00
FIBER 0,3 mm	103,61	180,91	221,71	406,56	428,36
FIBER 0,55 mm	56,92	102,95	149,40	231,03	243,77
FIBER 0,98 mm	131,18	229,04	333,07	515,06	550,18
FIBER 1mm	131,77	230,09	334,59	517,41	544,79
FIBER 1,48 mm	131,18	229,04	333,07	515,06	539,85
FIBER 1,5 mm	98,43	171,86	249,72	386,16	407,03
FIBER 1,96 mm	131,18	229,04	333,07	515,06	539,85
FIBER 3mm	72,26	230,09	158,38	515,06	263,37

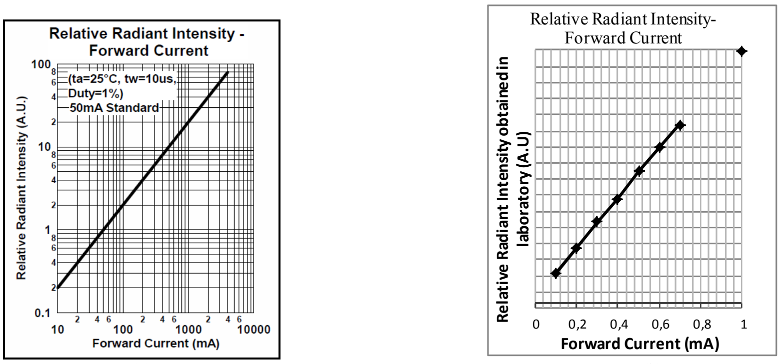
Table 2. *Total Power on 3,5 mm not accounting the packing factor loss (mW/mm^2)*

3.2 Experimental Results

Our numerical analysis is now compared to our numerical results to evaluate its validity. The total radiant intensity of the LEDs and fibers combinations numerically estimated for all the cases and measured only for six cases. Several combinations were studied in the laboratory and they have low or normal irradiance efficiency but these combinations have a scientific interest in the research. For instance, combinations Array LED 1 and LED 3 with the FIBER 3mm which provides very similar information about the final behavior of the 3,5 mm active fiber bundle endoscope. LED 3 was particularly interesting because it outperformed power output with almost all optical fibers.

Several measurements performed with the LED 1 were also interesting. LED 1 is one of the LED of the Array LED 1. To have a comparison about the behavior of one individual LED and the Array, some measurements were taken with the individual LED and with the array combined with 1,96 mm fiber.

Measurements were difficult perform due to thermal problems with the LEDs. For instance the forward current for this LED 3 is specified to 1000 mA and the thermal problems appear at 700 mA with our set up. Datasheet show a lineal behavior of the forward current, therefore, with measurements every 100 mA until 700 mA it is possible extrapolate and find the expected value at its maximum nominal current. Thermal management of LEDs can be improved by a proper thermal management, but this was out of the scope of this study.



(a) (b)

Figure 6. *LED 3 Relative Radiant Intensity vs Forward current. a)manufacture's datasheet b)results obtained in laboratory; the black points are the real measurement results and the isolated point is corresponding to the Relative Radiant Intensity is the one calculated from linear regression calculation of the other points.*

Combinations tested in laboratory are shown in the first and second columns in Table 3. The numerical results according to the values obtained from Table 1 are in the third column. Experimental measurements are obtained according with the methods explained in the section 3.1, and their corresponding values are defined in the fourth column. Relative error and the marginal experimental efficiency of the numerical result to experimental measurement is measured in the fifth and sixth columns, respectively.

LED	**FIBER DIAMETER(mm)**	**NUMERICAL RESULTS(mW)**	**EXPERIMENTAL MEASUREMENTS(mW)**	**RELATIVE ERROR (%)**	**MARGINAL EXPERIMENTAL EFFICIENCY(η_{exp})**
Experiments to measure the effect of fiber diameter					
LED 3	0,3 mm	2,95 mW	3,5 mW	16	1.19
LED 3	0,98 mm	40,47 mW	30,74 mW	32	0.76
LED 3	1,48 mm	89,34 mW	46,9 mW	90	0.52
LED 3	3 mm	188,24 mW	53 mW	255	0.28
Multiple effects					
LED 1	1,48 mm	51,65 mW	38 mW	36	0.74
ARRAY LED 1	3 mm	157,19 mW	55 mW	186	0.35

Table 3.*LED and fibers combinations results obtained in empirically in laboratory. The numerical results column show the results obtained in numerical analysis to compare with the empirical results.*

Marginal experimental efficiency (η_{marg}) accounts for additional experimental effects which have not been considered in our numerical analysis which can be related to fiber diameter by an exponentially decaying function for experiments of LED 3.

Fitting	Goodness of fit
f(x) = a • exp(-b • diameter)+c	
a=1.32	SSE: 9e-4
b=0.87	R-square: 0.998
c=0.18	RMSE: 3%

Tabla 4. *Fitting and goodness of fit value to plot the marginal experimental efficiency, where SSE: Sum of Squares Error and RMSE: Root Mean Square Error*

In Figure 7, we can observe the actual fitting to the marginal experimental efficiency (η_{marg}) to an exponentially decaying function.

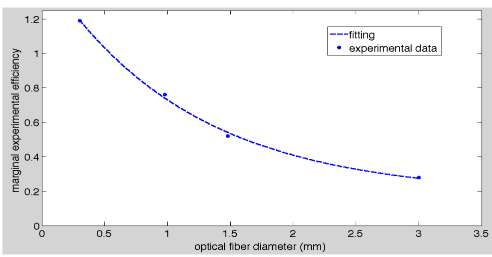


Figure 7. *plots the marginal experimental efficiency against the optical fiber diameter.*

The following table shows the experimental total irradiance (power per unit). The Total Power on 3,5 mm diameter fiber is obtained multiplying the Irradiance (power by unit area) and the endoscope fiber bundle section. The empirical total irradiance is employed in order to obtain the power on 3,5 mm diameter fiber bundle endoscope.

LED	FIBER	EXPERIMENTAL TOTAL IRRADIANCE	EXPERIMENTAL TOTAL POWER ON 3,5mm DIAMETER FIBER
LED 1	FIBER 0,3 mm	428,36 mW	585,44 mW
LED 3	FIBER 0,98 mm	550,18 mW	392,09 mw
LED 1	FIBER 1,96 mm	131,18 mW	122,76 Mw
LED 3	FIBER 1,96 mm	539,85 mW	149,55 Mw
LED 3	FIBER 3 mm	263,37 mW	74,10 Mw
ARRAY LED 1	FIBER 3 mm	229,04 mW	77,31 Mw

Table 5. *Total irradiance calculated from the empirical total power results and total power on 3,5 mm diameter fiber calculated from the empirical total irradiance.*

4.Discussion

Core sizes of fiber and numerical aperture have an important influence in the Radiant Intensity of the coupling as Table 1 shows us. The 3mm fiber has a numerical aperture of 0,50: the major core size and numerical aperture. The numerical analysis for the combination of this fiber with any LED has the biggest Radiant Intensity. For instance the combination of 3mm fiber with the LED2 is more than four times than the fiber 1,48mm[1], which accounts for four times less area. The 0,55 mm fiber has a small core diameter and has a smallest numerical aperture : 0,22. One of the less efficient combinations is this fiber with any LED.
The LED's most significant parameter is the half viewing angle. This parameter has a negative effect over the angular efficiencies and consequently over the total efficiencies. In the surface emission LED technology market there are a few ranges of half viewing angles available, hence the election of LED does not depend on this parameter. The second more important parameter is the emission power. The LED 3 is the most powerful one (Table 1, column LED 3 in comparison with the others columns). This LED has the most optimum fiber coupling it can achieve an output power at the end of the fiber in combination with 3mm fiber of 188,24 mW; this combination has an total efficiency of the 32% . Remarkably, coupling efficiency of a laser [4] with optical fiber is between 30% and 60%. Nevertheless the fiber coupled LEDs are a more cost effective solution than fiber coupled lasers.
The first step to obtain results to discuss was to calculate the Total Radiant, needed to determinate the Radiant Intensity. Radiant Intensity is calculated as the product of the Total Efficiency and the power LED emission in an circular section of 3,5 mm of diameter, this is the core section diameter of the endoscope's fiber bundle. The maximum value of Radiant Intensity in the numerical analysis is the 517 mW (Table 2, combination LED 3 and 200 microns fiber). Our objective was 1,5 W, four times the optimal Radiant Intensity calculated. This is the most important data because taking it in count, a solution for the IR light source is going to be analyzed.
Numerical analysis and experimental measurements have a disparity in their results. This disparity is modeled by the η_{marg} (Marginal Experimental Efficiency, table 4). The disparity between the numerical analysis and the experimental results is due to the simplicity of the mathematical model of the entire system. The differences could be accounted by some following reasons: The distance between the LED and the optical fiber could not be accurately measured and an assumption of a distance of 0,75mm had to be made. The measuring system is not properly modeled, some of the differences may be systematically introduced by the measurement system.
The maximum numerical Total Power is achieved with the combination LED 3 and fiber 0,2mm (Table 2, P= 517,87 mW). But we should correct this value with the marginal experimental efficiency. According to table 4 for a 0,2mm fiber the η_{marg} is 1,29. Therefore we estimate a Total Power for the combination LED 3 and fiber 0,2 mm of 712,08 mW, which remains to be experimentally measured and will be done in future experiments.

[1] Fiber 1,48 has an numerical aperture of 0,5

5.Conclusions and Future Work

The aim of this work was to develop an IR LED source alternative to the current laser based source. We have performed an exploratory study to determine the maximum amount of optical power of IR LED that can be coupled to a single fiber by pig tailing because at the time this work started it was the most scalable approach and might achieve high powers by adding multiple LEDs and fibers; and additionally, it has a good compromise of simplicity and affordability. Three LEDs and two LED arrays on one side and 10 optical fibers on the other were numerically combined in order to investigate the most efficient coupling. Six of these 50 combinations were studied in more detail in the laboratory with the specific purpose of achieving the maximum power coupling. These results were then compared to the numerical results and important limitations were found in the numerical assumptions. However, it was possible to correct for a single LED the effect of optical fiber in the overall coupling. New experiments are needed to further confirm this and more experiments with additional LEDs in the future might allow developing a more complete model and achieve an acceptable accuracy.

The maximum coupling efficiency of a LED and an optical fiber can be surprisingly high (even comparable to a laser) around 32% which demonstrates that main losses are produced by angular and geometrical effects. As expected, wide emission angle (or half viewing angle) of an LED is caused by the incoherent nature of LED radiation which cannot be efficiently focused even with high NA lenses as occurs with laser light. LED emission angle is very wide compared to typical optical fiber numerical apertures that cannot collect the total diverging light emitted by the LED, and hence, a lot of light energy fails to be transmitted by the optical fiber.

Importantly, these results offer a promising solution to achieve the desired output power (180mW at the input port of the endoscope’s light guide) for endoVV, but further efforts need to be addressed, which will be focused in LEDs with higher radiant power or other schemes of the state of the art like 1: an optimized assembly, in which the LED package is optimized installing the bare die and the optical fiber in a position closer to the emitting area would also enhance the performance of the coupling; 2: LED technology is being developed to sufficiently high radiant power to meet our necessities (several ultra powers LED arrays appeared in the market during this study) and this ultra power LEDs could be used as the main LED for *Direct LED coupling to fiber bundle input port*; and 3: on the other hand several interesting results have been reported by means of *multiple IR LED coupling with lenses*.

Finally, the proposed LED pig tailing in this work might be useful in other applications. It would be a good solution when illumination in small or confined spaces is necessary like microscopy, and a similar design is employed in telecommunication when the gain is not an important factor.

In summary, a preliminary and available numerical model of LED and fiber coupling has been developed and some limitations were successfully identified to correct them in the future, and most importantly, experimental results show that this approach offer a feasible implementation to achieve our objective for the endoVV.

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