# Analysis of optical crosstalk in flexible imaging endoscopes based on multicore fibers

Noé Ortega-Quijano*, Félix Fanjul-Vélez*, Irene Salas-García, Óscar Rubén Hernández-Cubero, José Luis Arce-Diego*

Applied Optical Techniques Group, Electronics Technology, Systems and Automation Engineering Department, University of Cantabria, Av. de los Castros S/N, 39005 Santander (Spain)

## ABSTRACT

Imaging endoscopes have enabled the development of minimally invasive procedures in a wide range of medical applications. Flexible endoscopes have additional advantages over rigid endoscopes. Remarkably, they have an enhanced capability of being guided through the internal conduits of the human body. The development of imaging endoscopes based on coherent optical fiber bundles have made high resolution fiber endoscopy possible. In the last years, multicore fibers have been proposed as an alternative to coherent fiber bundles for high resolution applications. Both types of structures entail several limiting factors. Among them, the most critical one is the optical crosstalk that takes place between the parallel contiguous fibers of the device, which provokes a worsening in the contrast of the images. Therefore it imposes a limit to the quality of the endoscopic system that must be avoided.

In this work, we present a theoretical model for the study of optical coupling in multicore fibers, which is based on an electromagnetic optics approach. This model is applied to the analysis of crosstalk within fiber imaging endoscopes. It includes the effect of core non-homogeneities and bendings. The essential equations of the model will be shown. These equations provide us with a theoretical basis that is subsequently applied to fiber endoscopes design. Therefore, we present a robust method for the adjustment of opto-geometrical parameters of the fiber in order to fulfil the quality requirements for a certain application. The key role of core diameter variations in the quality of the image will be specially highlighted.

**Keywords:** flexible endoscope, multicore fibre, optical crosstalk, bending effects, minimally-invasive imaging.

## 1. INTRODUCTION

Nowadays, endoscopes are widely used in medicine, being a basic medical device used in diagnosis, treatment and surgery applications, as well as in biopsy sampling [1]. Its potential is based on its minimally-invasive capacity, which results in non-surgical procedures. Therefore, the development of endoscopes has enabled to substitute the traditional invasive techniques by minimally-invasive techniques. As a result, the hospitalization time can be strongly reduced, and the recovery time of the patients becomes shorter.

Optical-fiber-based endoscopes enable the development of flexible endoscopes that can be guided through the internal conduits of the human body [2-3]. From the beginning, imaging fiber endoscopes were implemented with coherent fiber bundles, but the latest developments make use of multicore fibers in order to achieve ultrahigh resolution endoscopy, and are the aim of the present study.

Due to the parallel arrangement of the cores, optical crosstalk is produced within the fiber. The confinement properties of circular waveguides leads to a extension of the modal fields into the cladding, and the overlapping of the modal fields of a fiber with those of the surrounding fibers causes an interchange of optical power between them. The effect is a worsening in the contrast of the image, resulting in blurring, so it constitutes a critical factor in the design of these devices [4-9].

* ortegan@unican.es ; fanjulf@unican.es ; arcedj@unican.es ; phone +34942201545; fax +34942201873; www.teisa.unican.es/toa

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In this work, we present an analytical model for the study of optical crosstalk in multicore fibers for imaging endoscopy, and we apply this model to the optimized design of this type of endoscopes. Firstly, in Section 2 the theoretical approach used in this work will be presented. After that, Section 3 will show the behaviour of crosstalk in typical endoscopes as given by our model. Subsection 3.1 summarizes the fundamental parameters of such devices, subsection 3.2 presents the basic parameters involved in the design, and subsection 3.3 shows the curves that describe the behaviour of crosstalk as a function of the cores inhomogeneity. Finally, Section 4 presents the basic design curves that can be applied to optimize the design for any combination of opto-geometrical parameters of the multicore fibers used. Several aspects, like the effect of core diameter variations in the optical crosstalk and its significant role in the final performance of the endoscope, will be analyzed from the curves.

## 2. THEORETICAL MODEL

Crosstalk effects in multicore fibers are due to the confinement properties of circular waveguides. The radial distribution of guided modes can be described by first order Bessel functions within the core, and by second order modified Bessel functions in the cladding [4]. The behaviour of the modal fields in the cladding can be approximated by an exponential function for each mode. The overlapping of modal fields from different fibers results in a crosstalk effect that results in an optical power interchange between fibers.

Crosstalk can be studied by several techniques, like the modal expansion approach, methods based on reciprocity identity, and variational methods [4]. In particular, our study is based on a well-known variational method, Coupled Mode Theory (CMT), that has been widely used to analytically determine the optical crosstalk in coupled waveguides systems [5-6]. In this way, coupling between cores will be analysed by the summed effect of coupled modes using CMT.

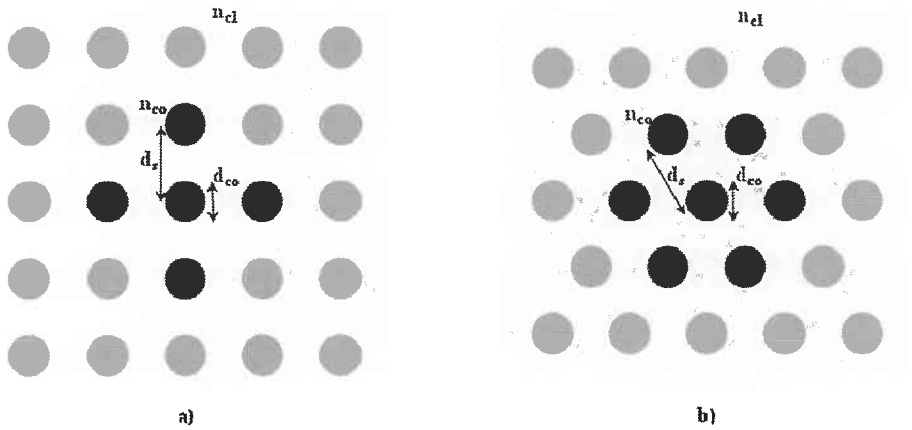


**Fig. 1.** Types of arrangement in multicore fibers. a) Square packing. b) Hexagonal packing. The parameters of the fiber are the core refractive index ($n_{co}$), the cladding refractive index ($n_{cl}$), the core diameter ($d_{co}$) and the intercore distance ($d_s$). The first ring of surrounding fibers has been highlighted. Proportions are arbitrary.

Firstly, we consider an arrangement of cores embedded in a homogeneous medium. The most usual type of arrangements are the square packing and the hexagonal packing [10-11], as schematically shown in Figure 1. However, this analysis is not constrained to any specific type of arrangement. As well as that, we assume a fiber parameter $V >> 1$. Then, taking into account nearest-neighbor coupling as shown in Figure 1, it can be proved that the total crosstalk power from an illuminated fiber to the surrounding fibers is given by [9]:

$$\frac{P_{ct}(z)}{P_{in}} \cong \frac{1}{2} G \left[ 1 - \operatorname{sinc} \frac{2}{\pi} \left( \frac{n}{G} \right)^{1/2} C_q z \right], \tag{1}$$

where $n$ is the number of surrounding fibers (which depends on the structural characteristics of the arrangements), $C_q$ is the coupling coefficient for mode $q$, and $G$ is given by

$$G = \begin{cases} F, & 1 \le n < 3 \\ F\left(1+\dfrac{1}{n}\right)^{-1}, & n \ge 3 \end{cases}. \tag{2}$$

In this equation, $F$ is the maximum crosstalk-power transfer, and follows the next expression [12]:

$$F = \frac{1}{1+\left(\dfrac{\Delta\beta}{2C_q}\right)^2}, \tag{3}$$

where $\Delta\beta$ is the difference between the propagation constant of the fibers involved in optical coupling. If the analysis is limited to inhomogeneities in the core size, the propagation constants difference can be calculated by

$$\Delta\beta \cong 2(2\delta)^{1/2}\frac{\Delta d_{co}}{d_{co}^2}\frac{U_q^2}{V}, \tag{4}$$

$\Delta d_{co}$ being the difference in the diameter of the cores, $d_{co}$ the average core diameter, $\delta$ the relative index difference between core and clad, and $V$ the normalized frequency. If the cores are identical, then $\Delta\beta = 0$ and $F = 1$. On the other hand, if there is a variation in the core diameter, the maximum crosstalk-power ratio diminishes. This effect will be analyzed in the next section.

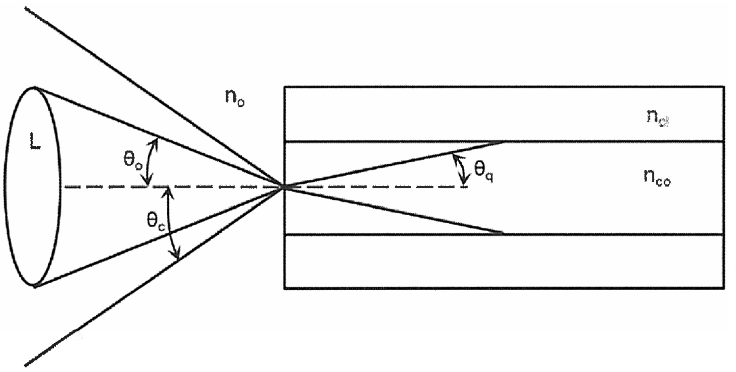


**Fig. 2.** Lens illumination of the fiber. $L$: focusing lens, $\theta_c$: complement of the critical angle, $\theta_o$: angle subtended by the lens, $\theta_q$: angle between the ray direction and the axis.

The equations for the coupling coefficient are rather complicated [6,13-14]. However, considering weakly-guiding fibers, approximate expressions for the field can be used to determine the coupling coefficient. It will be assumed that a lens system focuses a collimated beam of light on the core axis, as depicted in Figure 2, so that only meridional modes (i.e. the $HE_{1m}$ modes) are excited [6]. The coupling coefficient for these modes can be shown to be [9]:

$$C_q = \frac{2}{d_{co}}\left[\frac{\delta\left(1-S^2\right)^{1/2}}{\pi D V}\right]^{1/2} S^2 e^{-2V(D-1)\left(1-S^2\right)^{1/2}}. \tag{5}$$

where $D=d_s/d_{co}$ is the intercore distance to core diameter ratio. It has been taken into account that the core parameter $U$ can be related to the fiber parameter $V$ and to the angle $\theta_q$ between the ray direction and the axis by $U_q = VS$ for $V \gg 1$ [15], where $S=\sin\theta_q/\sin\theta_c$ and $\theta_q=\mathrm{asin}(\sin\theta_o/n_{co})$, $\theta_c$ being the complement of the critical angle and $\theta_o$ the angle subtended by the lens, as shown in Figure 2. We have used the approximate form of the modified Bessel function of the second kind for values of the cladding parameter [14], and the exact expression for the cladding parameter $W$, avoiding the approximation $W=V$ for large $V$ values used in other works.

The limitations of this analysis are a result of the approximations taken trough the analytical process. Therefore, it can only be applied to fibers with $V >> 1$. The fact that it neglects cross-mode coupling is not very relevant, as long as this effect has been shown to be negligible [5]. Other important factors to be considered in optimum design of fiber endoscopes are leaky modes and the fiber packing technique. Both issues have been studied by our group in some previous works [7-8].

## 3. CROSSTALK IN MULTICORE FIBERS

The analytical approach shown above can be applied to the study of crosstalk in multicore fibers. Among the different types of core arrangements, the hexagonal packing results in the higher cross-sectional active area, and therefore it is preferred by the main manufacturers. Consequently, we will focus on this type of arrangement.

### 3.1 Typical parameters

Despite the number of fiber manufacturers and the amount of endoscopes applications, the usual parameters of the fibers used in imaging endoscopes are usually delimited between some typical values [1,10-11,16]. The total diameter of the fiber is usually within the range of 0.5 up to 3 mm, being composed from roughly 5,000 to 50,000 individual cores. Although the first designs made use of optical fibers with diameters up to 250 µm, the latest developments for high resolution imaging make use of core diameters between 2 and 10 µm. The typical value for the core refraction index is 1.45, provided that silica fibers are used in order to transmit the visible spectrum with minimum losses. The normalized frequency of the fiber is usually in the upper limit of the weakly-guiding regime. The intercore distance to core diameter ratio ranges from roughly 1.2 to 1.6. Finally, the endoscope length can vary from 30 centimeters up to 2 meters, depending on the application. All these values are summarized in Table 1.

**Table 1.** Typical parameters of multicore fibers for flexible endoscopy.

| | Min. (typ.) | Max. (typ.) |
|---|---|---|
| **Total diameter** | 0.5 mm | 3 mm |
| **Number of cores** | 5,000 | 50,000 |
| **Core diameter** | 2 µm | 10 µm |
| **Core refractive index** | ≈1.45 | |
| **Intercore to core ratio** | 1.2 | 1.6 |
| **Endoscope length** | 30 cm | 2 m |

### 3.2 Design parameters

The analysis of optical crosstalk in fiber endoscopes and the subsequent design of these devices is usually performed by the study of two parameters: coupling efficiency and packing fraction.

On the one hand, the coupling efficiency constitutes the basic parameter to describe the crosstalk of an optical system. It is defined as:

$$CE = \lim_{z\to\infty} \frac{P_{ct}(z)}{P_{in}}. \tag{6}$$

It can be seen that this parameter is the fraction of power transferred between cores when modal stability has been reached, regardless the distance at which it takes place. Considering hexagonal packing, and using the expressions given in Section 2, the coupling efficiency can be readily shown to be

$$CE = \frac{3}{7}\left(1+\left\{\frac{1}{2}\left(\frac{\Delta d_{co}}{d_{co}}\right)\left[\frac{\pi D V^3}{\left(1-S^2\right)^{1/2}}\right]^{1/2} e^{2V(D-1)\left(1-S^2\right)^{1/2}}\right\}^2\right)^{-1}. \tag{7}$$

On the other hand, the packing fraction quantifies the active area of the fiber, i.e. the ratio of the cross-sectional area corresponding to the cores. It is given by the next expression [1,7-8]:

$$f_p = \frac{\pi}{2\sqrt{3}}\left(\frac{1}{D}\right)^2. \tag{8}$$

The packing fraction has an upper limit of 90.68% due to geometrical considerations derived from the fact that circular cores cannot completely fill the entire cross-sectional area without overlapping.

### 3.3 Crosstalk behavior

Taking into account the analytical model presented in Section 2, and the typical values of fibers and design parameters previously shown, the crosstalk behaviour in multicore fibers for imaging endoscopes can be analysed.

In Figure 3, the coupling efficiency as a function of the diameter variation percentage has been plotted for several values of *D*. We have considered a core diameter of 5 µm and a relative index difference of 0.01. It can be appreciated the strong impact of the core non-uniformity in the coupling efficiency of the system. If there is no variation in the diameter of the cores, the graph shows that the coupling efficiency is the same for all intercore distance to core rations, i.e. the optical crosstalk in the stationary coupling regime will reach the same value regardless of the intercore distance. From the other side, it can be appreciated that diameter variation values of less than 10% can provoke reductions in the coupling efficiency of several orders of magnitude, depending on the intercore distance. As an example, a core diameter variation ratio of 6% would produce a reduction of roughly 3 orders of magnitude in the coupling efficiency for an intercore distance to core ratio of 1.4. These results show that the core non-uniformity is an essential factor in order to diminish crosstalk in high resolution imaging endoscopes design.

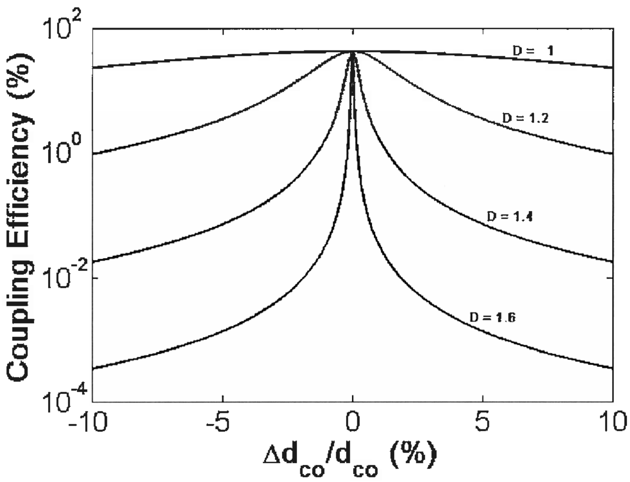


**Fig. 3.** Coupling efficiency as a function of the core diameter variation. A core diameter of 5 µm and a relative index difference of 0.01 have been considered. The curves have been plotted for a range of intercore distance to core diameter ratios from 1 (upper curve) to 1.6.

## 4. DESIGN CURVES

In this section, the presented approach will be applied to the optimization of practical fiber endoscopes design. Thus, a method for the accurate determination of the intercore distance as a function of the design parameters will be proposed.

Having shown that the core diameter variation has a strong impact in the coupling efficiency, we must now analyze the origin of such variation and quantify it. Several works have shown that the statistical variation in the size of the cores is due to the imperfection of the manufacturing processes [16-18]. The typical aspect of real multicore fibers is shown in Figure 4. The inhomogeneities between cores can be easily appreciated. Once the fiber is manufactured, the core variations has to be quantified [18]. Having determined this statistical parameter, the maximum coupling efficiency affordable in the endoscopic system must be fixed.

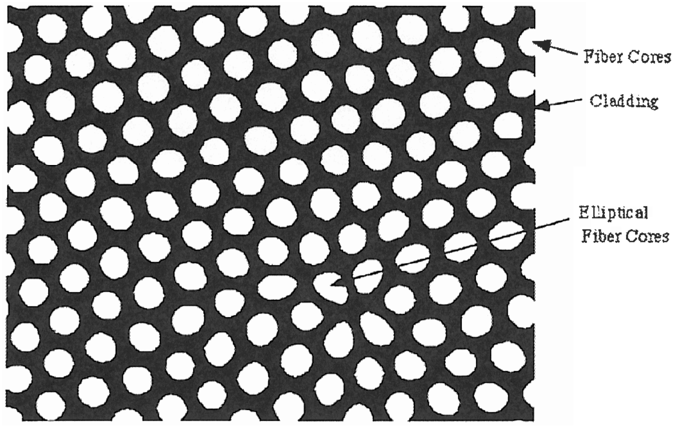


**Fig. 4.** Micrograph image of transversal structure of a typical multicore fiber [18]. The image has been thresholded. The inhomogeneity in the cores diameter can be observed.

In Figure 5, the fundamental curves in fiber endoscopes design are shown. The diameter variation ratio has been set to several values from 0.01% to 100%, although the typical value is around 10%. A maximum coupling efficiency of 0.01% has been fixed. From this Figure, the intercore distance can then be obtained as a function of the opto-geometrical characteristics of the fiber. As an example, for a core variation of 10%, the intercore distance should be roughly 1.2 times the core diameter in order to achieve the design conditions for a normalized frequency $V$ greater than 8. As a comparison, the value of $D$ for a maximum coupling efficiency of 1% (two orders of magnitude less restrictive) should be around 1.07.

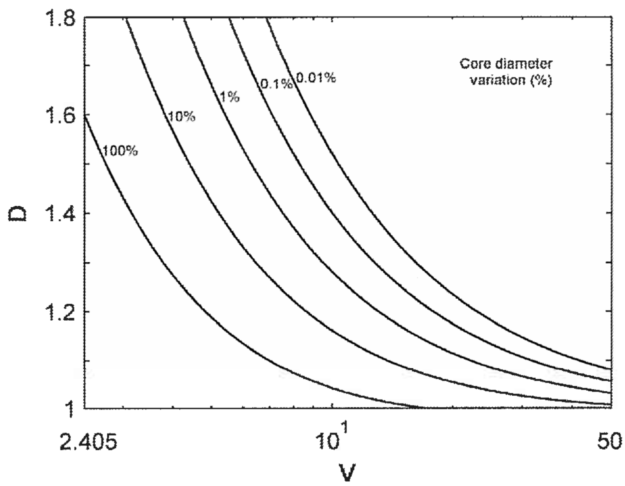


**Fig. 5.** Intercore distance to core diameter rate as a function of the normalized frequency $V$. A range of core diameter variations from 0.01% (upper curve) to 100% has been considered. The maximum coupling efficiency imposed to the system is 0.01%.

Once the intercore distance has been determined from the previous curves, the packing fraction can be analyzed in order to achieve a design with an equilibrium between crosstalk and active area. Figure 6 shows the curves for the packing fraction as a function of the fiber parameter $V$. These curves have been calculated for values of the coupling efficiency ranging from 0.01% to 10%, considering a core diameter variation of 10%. It can be appreciated that the most restrictive case results in a lower packing fraction as a result of the increased intercore distance needed. For example, the packing fraction for a normalized frequency $V$ of 10 and a coupling efficiency of 0.01% is about 68%, while it takes a value of 83% for a coupling efficiency of 1%.

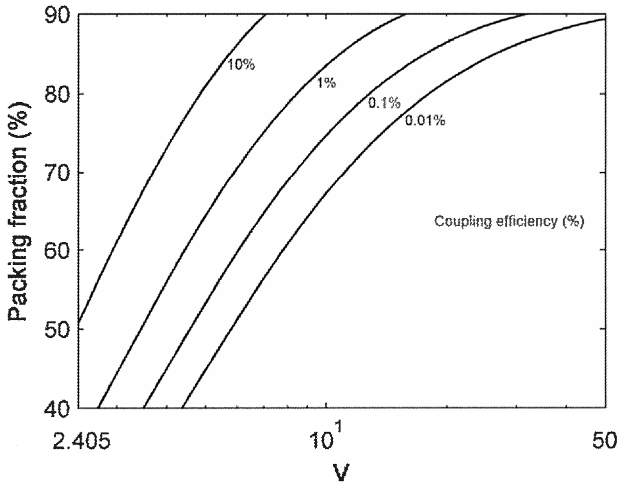


**Fig. 6.** Packing fraction as a function of the fiber parameter $V$. The curves correspond to a range of coupling efficiency from 0.01% (lower curve) to 10%. A core diameter variation of 10% has been considered.

## 5. CONCLUSIONS

This work presents a contribution to the study of optical crosstalk in fiber imaging endoscopes. A model has been proposed in order to analyze the behaviour of optical crosstalk in multicore fibers. Remarkably, the strong impact of the variations in the diameter of the core in the optical crosstalk of the system has been shown. After having summarized the typical parameters of the fibers used in imaging endoscopy, the theoretical model presented has been applied to determine the intercore distance to satisfy certain crosstalk design conditions. Finally, the essential design curves have been presented, that enable to adjust the fiber endoscope characteristics. A compromise must often be reached between coupling efficiency and packing fraction. The procedure shown above is extensible to any type of multicore fibers simply varying the opto-geometrical and design parameters involved.

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