Contrast limiting factors of optical fiber bundles for flexible endoscopy

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ABSTRACT

Medical endoscopy constitutes a basic device for the development of minimally invasive procedures for a wide range of medical applications, involving diagnosis, treatment and surgery, as well as biopsy sampling. Its minimally invasive nature results in no surgery, or only small incisions, which involves a minimal hospitalization time. The medical relevance of endoscopes relies on the fact that they are one of the most effective means of early stages of cancer diagnosis, with the subsequent improvement in the patient's quality of life. Flexible endoscopy by means of coherent optical fiber bundles shows both flexibility and a high active area. However, the parallel arrangement of the fibers within the bundle produces interference phenomena between them, which results in optical crosstalk. As a consequence, there is a power exchange between contiguous fibers, producing a worsening in the contrast of the image. In this work, this quality limiting factor is deeply studied. We quantitatively analyze crosstalk, performing several studies that show the limitations imposed to the endoscopic system. Finally, we propose some solutions by an analytical method to accurately determine the appropriate optical fibers for each particular design. The method is also applied to endoscopic OCT.

Keywords: imaging endoscope, fiber bundle, crosstalk.

1. INTRODUCTION

Nowadays, endoscopes are widely used in medicine, being a basic medical device whose main advantage is its minimally invasive capacity. Medical endoscopy is used in diagnosis, treatment and surgery applications, as well as in biopsy sampling [1-2]. In all these cases, the endoscope constitutes the basic component of a minimally invasive procedure that results in a drastic decrease of surgical interventions. As a result, medical praxis can be carried on with no surgery, or only small incisions, for a wide range of applications. In this work, we will focus on imaging endoscopy. The medical relevance of endoscopes relies on the fact that they are one of the most effective means of early stages of cancer diagnosis, with the subsequent improvement in the patient's quality of life. Among all the different types of imaging endoscopes, those which are based on optical fibers show an important advantage: flexibility. In particular, coherent fiber-bundle-based endoscopy exhibits both flexibility and a high active area, which make it a suitable option for imaging purposes. The parallel arrangement of the fibers within the bundle produces optical power crosstalk between contiguous fibers, causing a reduction in the contrast and consequently worsening the quality of the final image. Therefore, crosstalk in this type of endoscopes will be analysed in this paper. The relationship between crosstalk and both the length and the opto-geometrical characteristics of the fiber bundle will be accurately established. Finally, several design considerations will be shown in order to maximize the quality of the system. In this work, the effect of curvatures in the bundle has not been taken into account, as long as the critical radius of the fibers is extremely low in comparison with the typical curvatures found in medical praxis [3]. Other important factors to be considered in optimum design of fiber-bundle-based endoscopes are leaky modes and the fiber packing technique. Both issues have been studied by our group in some previous works [4-5].

In order to study these aspects, this work has been structured in several sections. In section 2, we will analyse the crosstalk in endoscopes based on fiber bundles. First of all, in subsection 2.1 we will present the analytical expressions for the ideal case. After that, subsection 2.2 will show the appropriate modifications to be included in the case of imperfect optics. Finally, subsection 2.3 analyses the situation for fibers with different diameters. In section 3, we present a typical situation in which it becomes necessary to determine the size of cladding needed to satisfy some design conditions in terms of maximum crosstalk at a given distance. After that, section 4 shows the application of all these

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principles to another field of application of endoscopes: Endoscopic Optical Coherence Tomography. The features required for this application will be discussed, and a subsequent study of the cladding needed will be carried on. Finally, section 5 summarizes the most important issues to be taken into account regarding the crosstalk in imaging endoscopes.

2. CROSSTALK IN FIBER-BUNDLE-BASED ENDOSCOPES

There exist two different types of fiber bundles, according to the arrangement of the fibers: disordered bundles, which are used exclusively for illuminating purposes inside the human body; and well-arranged or coherent bundles, in which the fibers are well arranged, that are used for optical imaging as they maintain the spatial relationship of the image taken [6]. Crosstalk is a quality limiting factor because it causes a power exchange between contiguous fibers, which in turn causes a worsening in the contrast of the image. Therefore, it has a negative impact in the quality of the system, so it must clearly be avoided. The parallel arrangement of the fibers in coherent fiber bundles causes optical crosstalk due to imperfect confinement of the modal fields within each fiber [7]. The strength of crosstalk depends on the overlap of these fields, so the size of the cladding directly determines the protection against interferences.

2.1 Ideal optics

It is assumed that a lens system focuses a collimated beam of light on the fiber axis. Considering an hexagonal arrangement of the fibers within the bundle [4-5, 8], the amount of interferent power that appears in a fiber as a result of the optical coupling coming from the six surrounding fibers, each one illuminated with a concrete power P_{in}, is

$$\frac{P_{ct}}{P_{in}} \cong \frac{3}{7}\left(1-\frac{\sin\sqrt{7}L}{\sqrt{7}L}\right). \tag{1}$$

In the previous equation, L is a dimensionless parameter related to the opto-geometrical parameters of the fiber, which can be expressed as

$$L = \frac{4\theta_c Z}{d_{co}}\left(\frac{\theta_m}{\theta_c}\right)^2 \frac{e^{-2V(D-1)}}{(\pi VD)^{1/2}}, \tag{2}$$

where, Z is the distance along the fiber axis, $D=d_s/d_{co}$, being d_s the distance between cores and d_{co} the core diameter, and $\theta_m=\mathrm{asin}(\sin(\theta_o)/n_{co})$, where θ_o is the angle subtended by the lens [9]. From these equations, it is observed that the coupling power is inversely proportional to V and D parameters. Therefore, crosstalk is inversely proportional to the core diameter, to the acceptance angle, and obviously to the size of the cladding, and it is directly proportional to the wavelength. This is directly due to the confinement properties of the fiber.

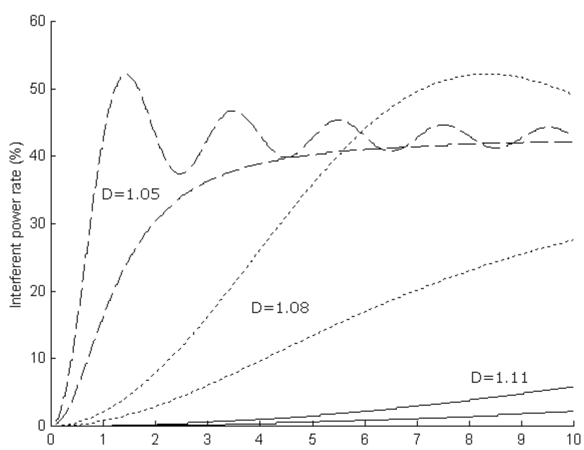

Fig. 1. Interferent optical power rate against the position Z along the fiber axis, for fibers with n_{co}=1.45, d_{co}=100 μm, δ=0.001, λ=700nm, for an hexagonal arrangement of optical fibers inside an imaging endoscope. The results for several values of D (1.05, 1.08 and 1.11) have been plotted. For each value of D, the upper curve shows the interference in an ideal optics case, while the lower curve corresponds to the imperfect optics case with K=2.

2.2 Imperfect optics

In the imperfect optics case, the illumination suffers some modifications in comparison to the ideal situation. As a result, the optical coupling follows this relationship

$$\frac{P_{ct}}{P_{in}} \cong 3\frac{L^2}{7L^2 + K^4}\,, \qquad (3)$$

where, K is the degree of imperfection of the illumination system. In Figure 1 we have plotted the crosstalk curves for a typical case. We have considered the parameters involved in endoscopic imaging. The typical core radius of the fibers used is roughly between 25 and 200 µm. The need to deal with visible wavelengths to perform imaging makes silica core optical fibers a proper choice. Therefore, a core refraction index of 1.45 has been considered. As well as this, these type of fibers are mostly weakly-guiding fibers, so a value of the relative difference between the refractive indexes ($\delta = (n_{co}-n_{cl})/n_{co}$) of 0.001 has been fixed. The near infrared edge of the visible spectrum constitutes the limiting case, so a wavelength of 700 nm has been chosen for the calculations. The same dot-style curves correspond to a certain value of parameter D. For each value of parameter D, the upper curve shows the interference in an ideal optics case, while the lower curve corresponds to the imperfect optics case. We have chosen a value of K=2. In all the examples that follow, we are considering that the angle subtended by the lens is half the acceptance angle.

It can be observed that the crosstalk power increases with the distance in a slightly oscillatory way, till it reaches an interferent power rate that is maintained for higher distances. From Figure 1, it is obvious that the crosstalk is reduced when the cladding increases. As well as this, it can be seen that in the imperfect optics situation the crosstalk is lower than in the ideal optics case. This is due to inhomogeneous modes excitation in the illuminating system, which causes a subsequent reduction in the mode coupling effects. According to the curves plotted, we can consider that the crosstalk power rate for a value of D=1.11 and for the fiber considered is almost negligible at a distance of 2 meters. Such a distance is large enough to most of the medical applications involving endoscopes. In this situation, the cladding constitutes 18.83% of the fiber cross-sectional area. Different cladding sizes would be obtained for fibers with other opto-geometrical parameters.

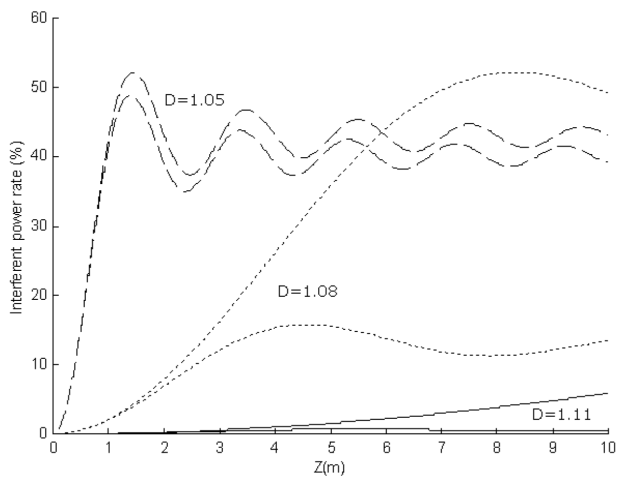

Fig. 2. Interferent optical power rate as a function of Z, for fibers with n_{co}=1.45, d_{co}=100 µm, δ=0.001, λ=700nm, and D (1.05, 1.08 and 1.11). For each value of D, the upper curve shows the interference for a bundle of fibers with identical diameters, while the lower curve corresponds to unequal diameters with a fractional difference of $\Delta d_{co}/d_{co}$=0.01%, i.e., Δd_{co}=10 nm.

2.3 Variation in the diameter of the fibers

So far, it has been considered that the diameters of the fibers were invariable. However, crosstalk is very sensitive to variations in the diameter of the fibers within the bundle. Diameter variations have a double effect: it diminishes both the maximum crosstalk and the crosstalk power rate of the stationary state. In this case, the crosstalk power is given by

$$\frac{P_{ct}}{P_{in}} \cong \frac{3F}{7}\left(1-\frac{\sin\sqrt{\frac{7}{F}}L}{\sqrt{\frac{7}{F}}L}\right), \tag{4}$$

where, F can be expressed as $F = \frac{1}{1+X^2}$, being X a parameter that is obtained with the following equation:

$$X = \frac{1}{2}\sqrt{\pi D V^3}\,\frac{\Delta d_{co}}{d_{co}} e^{2V(D-1)}. \tag{5}$$

Figure 2 shows the crosstalk power for several values of D in a situation analogous to that of Figure 1. Here, the upper curves are the same, while the lower curves show the crosstalk for a variation in the diameter of the fibers of $\Delta d_{co}/d_{co}$=0.01%. It can be observed that the general behaviour of crosstalk is the same as in the previous section. Imperfections in the optics have not been taken into account. Again, a cladding size of less than 20% is enough to achieve a negligible crosstalk power rate. It is important to note that a tiny difference between diameters can drastically reduce crosstalk, as will be seen in the following sections.

3. DETERMINATION OF THE CLADDING SIZE

Having studied the behaviour of optical crosstalk in the previous sections, we will apply this knowledge to face some design issues. In most cases, the device length is determined a priori according to the application, and a limit in the interferent optical power is fixed in relationship to the maximum worsening of the contrast for each particular situation. The final objective is to determine cladding size needed to satisfy the crosstalk limit. Figure 3 depicts the fiber cross-sectional area corresponding to the cladding, as a function of the core radius, for a relative index difference of 0.001 and 0.01, which corresponds to the range of weakly-guiding fibers. The condition imposed is that the percentage of crosstalk power for an endoscope length of 2 meters must have a maximum of 1%. The upper curves are the ideal optics case, while the lower curves correspond to a variation in the diameter of the fibers of $\Delta d_{co}/d_{co}$=0.1%. As it can be seen, both the core diameter and the relative index difference have a dramatic impact in the cladding needed to maintain the optical crosstalk into the acceptable limit. It is clear that a very small variation in the diameters can provide a marked reduction in the cladding area needed, therefore increasing the active area of our system while maintaining the quality.

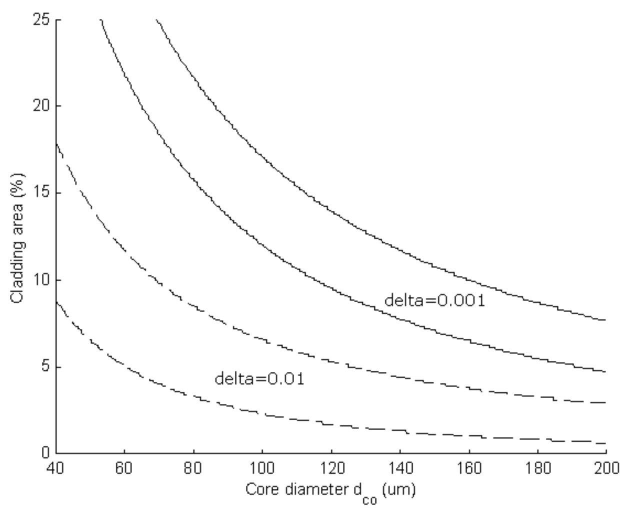

Fig. 3. Cladding area as a function of the core diameter for weakly-guiding fibers (δ=0.001 and 0.01) arranged in an hexagonal structure. The condition imposed is a maximum crosstalk of 1% at z=2 meters. It has been considered a fiber with n_{co}=1.45, and the calculations were made for λ=700 nm. For each value of δ, the upper curve corresponds to fibers with identical diameters, while the lower curve corresponds to unequal diameters with a fractional difference of $\Delta d_{co}/d_{co}$=0.1%, i.e., Δd_{co}=100 nm.

4. ENDOSCOPIC OPTICAL COHERENCE TOMOGRAPHY

As well as for imaging purposes, endoscopes have found other powerful applications. One of them is in the field of Optical Coherence Tomography (OCT), resulting in the so-called endoscopic OCT (EOCT). It has been shown that fiber bundles can be used in order to perform EOCT measurements [10]. This application has a huge potential, as long as it widens the fields of application of OCT [11-12]. The biggest challenge in EOCT is to maintain the ultrahigh resolution already achieved in bulk devices. Therefore, in order to achieve a high lateral resolution, it is crucial to make use of small core fibers, as the lateral resolution directly relies on the core spacing. It has been shown that small core radius implies high crosstalk, so the cladding size is an important subject in such applications. In Figure 4, the center-to-center distance (i.e. the total diameter of the fiber) has been plotted as a function of the core diameter. The upper curves are those of the ideal optics situation, while the lower curves correspond to a variation in the diameter of the fibers of $\Delta d_{co}/d_{co}$=0.1%. The crosstalk limit fixed is 1% of interferent power for a length of 2 meters. In this case, the wavelength takes a typical value among the wide range of light sources employed in OCT applications: we have considered a central wavelength of 1310 nm.

From Figure 4 it is clear that the total diameter as a function of the core diameter follows a constant slope straight line for high core diameter values, while it shows a non-linear behaviour for small diameters. In EOCT applications, it seems highly inadvisable to use markedly weakly-guiding fibers for the endoscopes bundles in the case of invariable diameters, because the center-to-center spacing is dramatically increased, worsening the lateral resolution. Instead of that, fibers with a significant different between the index of the core and the cladding should be chosen, in order to maintain the lateral resolution of the system in a high resolution regime. We should remark that the limitation imposed has been fixed for an endoscope length of 2 meters, which could be excessive for certain applications. For smaller endoscope lengths, the worsening of the lateral resolution would follow an analogous behaviour, but would be less noticeable. We can also observe that the variation of the diameter of the fibers can strongly diminish the size of the cladding needed. Therefore, increasing the fractional diameter difference it would be possible to use weakly-guiding fibers while achieving an ultrahigh lateral resolution, i.e., a very small center-to-center spacing.

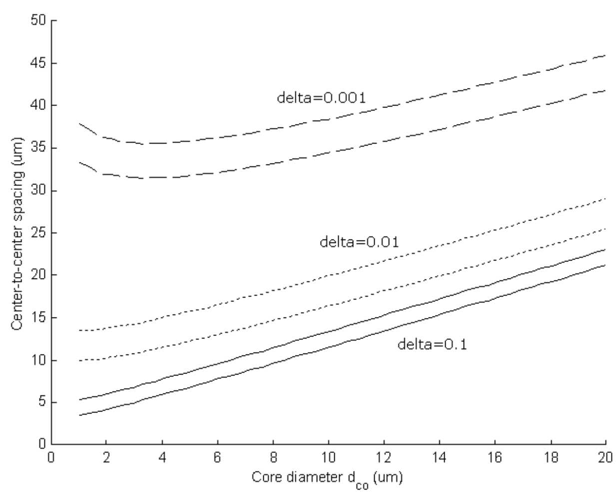

Fig. 4. Total diameter against core diameter to achieve a maximum of 1% crosstalk power for an endoscope length of 2 meters, in the case of fibers with n_{co}=1.45. The calculations have been made for δ=0.001, 0.01 and 0.1, and for a wavelength of 1310nm. For each value of δ, the upper curve corresponds to fibers with identical diameters, while the lower curve corresponds to unequal diameters with a fractional difference of $\Delta d_{co}/d_{co}$=0.1%, i.e., Δd_{co}=100 nm. The core diameters considered correspond to those needed for endoscopic OCT applications.

5. CONCLUSION

The effect of crosstalk in fiber bundles for imaging endoscopy has been studied. We have presented the behaviour of crosstalk as a function of the distance and the opto-geometrical parameters of the optical fiber. The relationship between the size of the cladding and the amount of optical interference has been shown. The equations in the case of imperfect optics have also been shown, proving that an imperfect illumination reduces the crosstalk as a result of inhomogeneous optical modes excitation. As well as that, we have studied the effect of a certain variation in the diameter of the fibers, given by the fractional diameter difference between the fibers within the bundle. It has been shown that it can be a powerful method to strongly reduce crosstalk. Finally, we have briefly presented a design procedure in which we determine the size of cladding needed to satisfy some crosstalk conditions. Here, the effect of variations in the diameter of the fibers is also shown, demonstrating that it is indeed an effective way to reduce the cladding area while maintaining the quality of our system in terms of crosstalk.

After that, the role of crosstalk in endoscopic OCT by means of fiber bundles has been analysed. We have applied the previous study to the typical parameters involved in EOCT. In particular, the wavelength of interest and the core radius are very different to those of imaging endoscopes. The importance of the center-to-center spacing has been highlighted, and subsequently the determination of the cladding size has been shown to be a crucial step in order to maintain a high lateral resolution. Therefore, we have stated that weakly-guiding fibers are not the best option in this situation. However, it has been shown that variations in the diameters of the fibers can significantly reduce the crosstalk, so it would be possible to use weakly-guiding fibers with small fractional diameter differences in order to achieve a high lateral resolution system with a negligible crosstalk.

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