Launching coupling efficiency calculations from optical systems to single mode fibre.

Manual

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Abstract

The aim of this short report is to let a trace of the work done during 10 weeks at the Czech Thechnical University of Prague (Czech Republic) at the Faculty of Nuclear Physics in the department of Physical Electronics under the responsability of Pr. Fiala. This report resumes the problem to solve and the implemented solution. The problem is to make a numerical code to compute the coupling efficiency of ligth that passed through an optical system to a single-mode fibre. We focus on the interface between the exit pupil plane of the optical system and the fiber. We suppose we know the field distribution of the source at the exit-pupil plane, the total aberration at the same plane and the relative position of the fiber with this plane. The solution is based upon the farfield point of view [3] that permits to rely on with already existing ray-tracing programs for the computation of the incoming distribution of ligth. Moreover this permits to manage general aberration that is harder if the near-field point of view is used.

The code itself is written in ANSII C/C++ and was tested on an Indy Sillicon Graphics under unix system.

Contents

Chapter 1

The problem: principles and theory

1.1 Description

The problem we have is to solve is the coupling efficiency between an optical system and a single-mode fibre. We focus on the interface between the exit-pupil plane of the optical system and the entrance of the fibre. We suppose that parameters we need at the exit-pupil plane from the source are known. That is we know the geometry of the domain of the exit-pupil, the normalized distribution of the field or of the intensity and the wave front aberration due to the optical system.

We will call global system, the optical system and the input fibre end that are in a well defined position to each other.

1.2 Basic principles

The first principle to compute the coupling efficiency of our global optical system is that if the distribution field of the input ligth match to the distribution field of the propagating mode of the fiber we have a coupling efficiency of 100%. If there is mismatch due to linear or angular offset or to aberration, the coupling efficiency will less than 100%. We must also take into account losses du to the reflected part of the incoming beam at the endface of the fiber. The value of the coupling efficiency is given by an integral over the infinite plane situed at the fiber end. This integral is called the "overlap integral".

There are two points of view for computing this integral. Firstly we can stay at the fiber end. We then need to deal with near-field distribution The main disadvantage of doing this is that we need to know the near-field distribution of the source. Often we only know the far-field distribution of the source, that is what is given by ray-tracing program. The near-field distribution could be obtain from this far-field distribution but we'll need to use fast fourier transform that must be manipulate precisely. Another disadvantage is that it is difficult to manage aberration that is a very interesting parameter for a configuration we could encounter in a real system. Secondly we can have a far-field point of view and do the calculation of the overlap integral in the exit-pupil plane of the optic system to be coupled to the fibre. This has the advantage that missed to the near-field point of view: we can obtain experimentally and very easylly the field to do checking or even to have input data for the code. We can also manage aberration that is often a output parameter of ray-tracing program. From now, we will examine this point of vue that is describe in [3].

1.3 Theory

All the theory is acurately describe in the reference [3]. We will only resume without the parts we we need in the case of our particular conditions. We try to keep the notation used in [3] almost for all. The most important execption if for the cœfficient of coupling. We used T for the transmission cœfficient and C for the cœfficient of coupling that includes T wheras in [3] there didn't take into account of the transmission cœfficient.

1.3.1 Geometrical configuration

General overview of the global system

The geometrical configuration of the general system is as on the figure 1.1. A diverging beam of a laser source in entering in an optical system that couples the light into a single-mode fibre. The laser source and the optical system interested us as the resulting distribution field in the exit pupil plane. The receiving fibre lies near the image of the source.

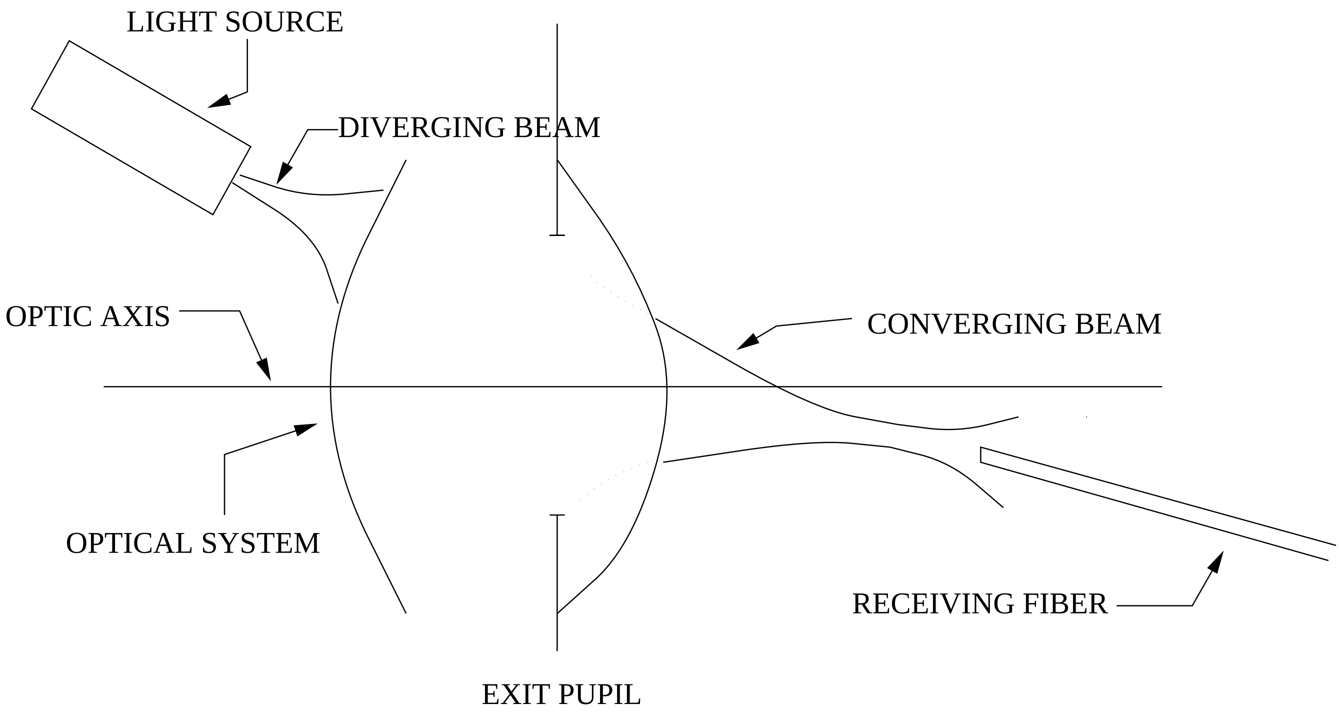


Figure 1.1: General configuration of the system use for the coupling int a single-mode fibre.

Definitions

Figure 1.2 depicts the general geometry of the system that interests us i.e. the space between the exit-pupil plane and the plane where lies the receiving fibre. Figure 1.3 details more precizely the linear fibre misalignments. Finally figure 1.4 describe details the angular mismatches of the fibre.

Here is the list and a short description of the terms used in theses pictures.

- The exit-pupil plane
  e is the exit-pupil plane where are made the calculations of the overlap integral.
  Q' is the axial point on the e-plane.
  $\Psi'_R(X'_e)$ s the far-field distribution of the receiving fibre.
  $\Psi'_S(X'_e)$ the far-field distribution of the output of the optical system.
  $\mathbf{X}'_{OS}$ and $\mathbf{X'_{OR}}$ are the centers of the field distribution respectively of the source and of the receiving fibre in the e-plane.

- The source-image plane
  The source-image plane is situated at a distance z' of the e-plane.
  S' is the paraxial image point, its coordonates represented by η'.
  R' is the radius from Q' to S.

- The fibre plane
  i is the plane where lies the endface of the receiving fibre. It is situated at a distance z_i from the exit-pupil plane.

- The fibre position
  I is the point of the location of the fibre endface.
  $\eta_{\mathbf{i}}$ represents the (x,y) coordinates of I in th i-plane.
  $\mathbf{f_R}$ is the unit vector parallel to receiving-fibre axis.
  R_i is the radius from Q' to I.

- The fibre misalignment (see fig. 1.3 and 1.4)
  Linear lateral misalignment is $\delta\eta' = \eta' - \eta_i$
  Linear radial misalignment is $\delta R' = R' - R_i$
  Angular misalignments $\delta\theta_x$ and $\delta\theta_y$ are due to the orientation of the vector $\mathbf{f_R}$ compare with the optic axis.

1.3.2 Hypothesis

Our assomptions about the systems are:

- Monochromatic and coherent light
  We deal with coherent light at a unique wavelength. We don't treat incoherent light or ultra-short laser pulse that have a largespectral domain.

- Polarisation
  We suppose the source light is linearly polarised.

- Beams shape
  We suppose source beam to be Gaussian ones with circular section for now. Beam with elliptical section will be implemnted later. This hypothesis is not restrictive in a theorical way but this is usually the type of laser beam.

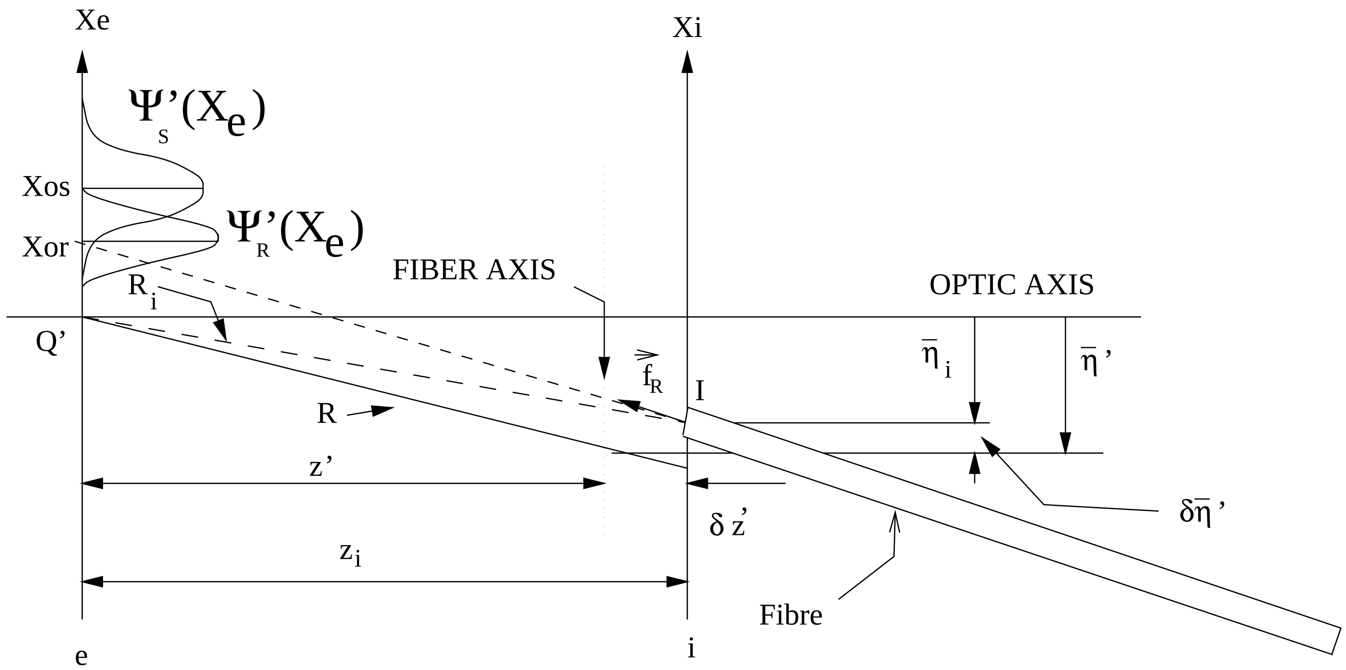


Figure 1.2: Detailled description of the geometric configuration between the exit-pupil and the fibre end face.

- Fibre type
  The type of fibre we deal with are step-index or parabolic index ones. In the Gaussian approximation of output beam from the fibre we make, we take account of the fibre type.

- Fibre endface
  We suppose that the fibre endface is perfectly cutted perpandicularly to its axis.

- Relfection at the fiber endface
  We approximate the transmission factor T to be the one for an homogeneous plane wave incident normaly on a plane boundary between two media with different refractive index. For the refractive index of the fibre, we take the average value of the clading index and of the core index [2]. The formula of t is very simple:

$$T = 1 - \left(\frac{n_{medium} - n_{fibre}}{n_{medium} + n_{fibre}}\right)^2.$$

  For example with air ($n_{air} = 1$) and a silice fibre ($n_{medium} = 1.5$) we have T = 96% i.e. -0.18 dB.

- Distribution field
  We deal with complex far-field distribution. These field distribution are normalized i.e. if $\Psi(\mathbf{X})$ is the distribution field then the total power is unity: $\int |\Psi(\mathbf{X})|^2 d\mathbf{X} = \mathbf{1}$ ($\mathbf{X}$ represents the cordinate vector of the plane we are interested in). This implies that the window we use for the calculations be large enough compared with the size

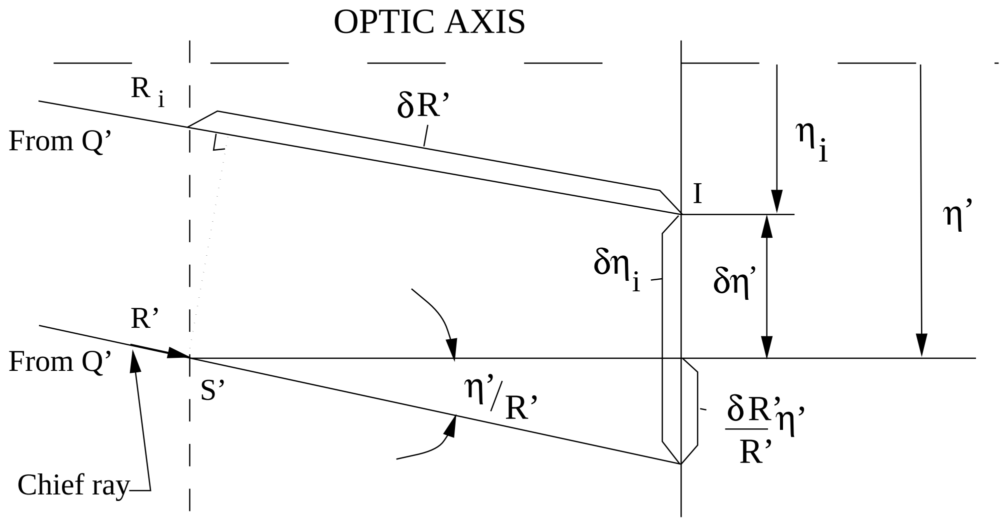


Figure 1.3: Image-plane geometry, defining linear fiber misalignements $\delta\eta_i$ and $\delta R'$ and emphasizing the diferecnes between η' and η_i and between $\delta\eta'$ and $\delta\eta_i$

s of the beams. If you have a window smaller than two times the biggest beam size then calculations may be not very precise because of the non-normalized field. If the window is too big (tells more than four time the bigger beam size) calculation cal also be not precise but because of numerical truncation. A good window size is between two and three times the bigger beam size.

- Aberration
  Wave-front aberration are defined as the optical path difference $W(X'_e)$ between the actual wave-front Σ' existing int he exit-pupil and an ideal spherical reference wave-front that converge toward the point I where is located the fibre endface. The total aberration $W_{tot}(X'_e)$ is the sum of aberration of the optical system $W_{syst.opt.}(X'_e)$ and of the aberration due to the fibre misaligment $W_{fibre}(X'_e)$. This last one is a real one in the sens that it causes coupling losses at the receiving fibre.

- Apertume stop
  The total aberration $W_{tot}(X'_e)$ is the sum of aberration of the optical system $W_{syst.opt.}(X'_e)$ and of the aberration due to the fibre misaligment $W_{fibre}(X'_e)$. This last one is a real one in the sens that it causes coupling losses at the receiving fibre. The wave front is taken in reference with the sphere centered on the fiber endface and that passes through Q' the intersection of the exit-pupil plane with the optic axis. We suppose te apertume stop is bigger than the window we use in the exit-pupil plane.

Under these asumptions, the general coupling efficiency equation for optics in single-mode fibre is

$$C = T * |\int \Psi'_S(X'_e - X'_{OS}) exp(-ikW_{tot}(X'_e))\Psi'_S(X'_e - X'_{OS})|^2.$$

This is the overlap integral that we compute in the numerical routine.

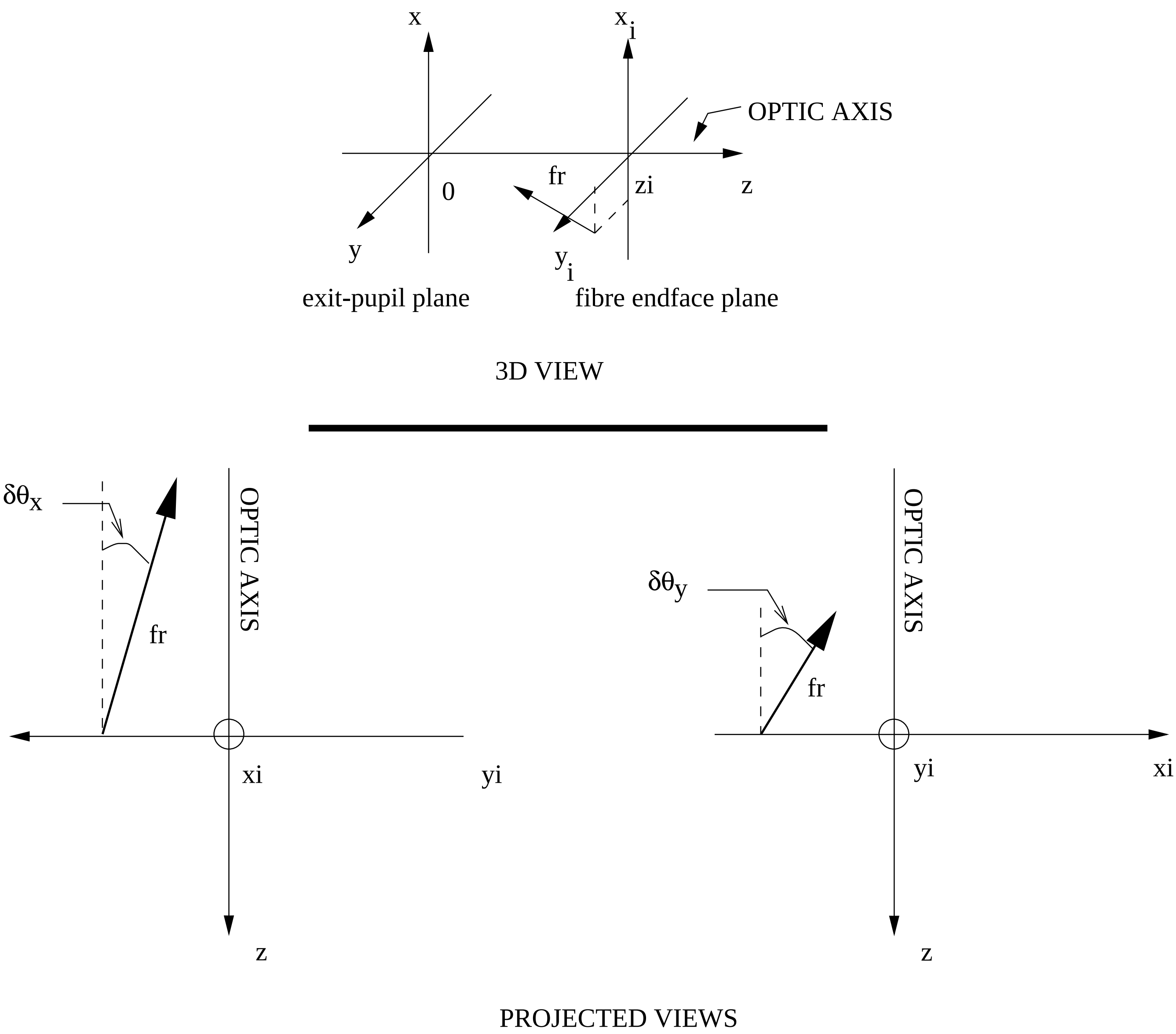


Figure 1.4: Description of the angles $\delta\theta_x$ and $\delta\theta_y$ of the angular misalignment of the receiving fibre.

Chapter 2

Structure of the program

The program is written in ANSII C/C++ in a structured programming. All the files and directories are in the father directory CSMF that is the contraction of Coupling to Single-Mode Fibre. An organigram of the hierarchy of the directories can be seen in the figure 3.1 of the Annexe.

In this chapter, we will discuss of the containing of the differents directories. We will begin by the detail descipirition of the files of the *SRC* directory and finish with the description of *DATA_IN* and *DATA_OUT* directories and the way to use the code. Besides these directories, there is the *DOCUMENTATION* directory that contains the LaTeXsources files and the PostScript formular of this report. Then we will present the program from a pratical view.

2.1 SRC directory

This directory contains all the sources (.c++ and .h files), the makefile (under Unix systems) and the executable code: Coupling. The .h files contain the declarations of the function of the .c++ corresponding files. All the files are fully commented and the references cited if needed. We tried to respect the notation of the main article [3] of the bibliography on which the theory of the code is based.

- *coupling.c++* is the main program. It essentially manages with input and output and use functions of the other files. You can see a simplified organigram of it in the figure 3.2 of the Annexe.

- *coupl_eff.c++* is the file were are the functions that actually compute de the coupling efficiency.

- *algebra.c++* manages addition of complex matrix.

- *exit_pupil.c++* contains functions to compute $\Psi'_R(X'_e)$ far-field distribution in the exit-pupil of the receiving fibre and $\Psi'_S(X'_e)$ the far-field distribution of the output of the optical system. We can have normalized circular Gaussian distribution. Ther is also a function to compute the aberration due to the receiving fibre. In fact it is the distribution of aberration in the exit-pupil.

- *memories.c++* contains functions to facilitate the dynamic memory allocation and free of the complex matrix.

- *params.c++* contains functions to compute parameters of the Gaussian beam of the receiving fibre such as the waist w_0, the Rayleigh distance Z_R and so on. This file also contains function to compute aberration parameters to be use with closed form formula or with the overlap integral.

- *read_params.c++* contains functions to read input parameters from the user. These parameters are in files the directory *DATA_IN*. We will describe theses files in details in the "DATA directories" section.

- typedef.h contains the declarator of a structure to keep the one dimension limits of the window in the exit-pupil.

2.2 DATA directories

In this section we describe the contains of the input and output files that are in *DATA_IN* and in *DATA_OUT* directories. Files in *DATA_IN* are all ASCII files ther is a unique numerical value for each line. In *DATA_OUT* the result file is also in ASCII form . The first part of the files' names is related with the contains, the suffixes are *prm* for input parameters and *out* for output of results.

All the examples of files in the following text are extracted from a unique and complete example.

2.2.1 DATA_IN

a) *exit_pupil.prm*

This files contains the size in pixels (integers) of the window of the exit pupil, n_x and n_y. The next four number are the real coordonates in x_{min}, x_{max}, y_{min} and y_{max}. To end, we have the size in x and in y of the incoming Gaussian beam w_{0x} and w_{0y} and the coordonates of the centre of the beam X_{OS} and Y_{OS}.

Here is an example of file:

```
32
32
-5500.0
5500.
-5500.
5500.
2500.
1600.
-300.
500.
```

b) *intr_fibr.prm*

This file contains intrinsic parameters of the fibre. There is in order the refractive index of the core n_{core} and of the clad n_{clad}, diameters of the core d_{core} and of the clad d_{clad} and an integer $fiber_{type}$ that code the type of fibre use. Now there are two type of possible fibre: step index (0) or parabolic index (1). We need these parameters to compute the waist of the fundamental mode of the fibre.

Here is an example of file:

```
1.460
1.457
10.
100.
0
```

c) *light.prm*
This file contains the free wave length of the laser light used λ_0 and the refractive index that is between the optical system and the fibre n_{medium}.

Here is an example of file:

```
1.3
1.
```

d) *source_image.prm*
This file contains the coordonates of the position of the paraxial image point S' i.e. η' and z'.

Here is an example of file:

```
-10.
5.
20000.
```

e) *pos_fibre.prm*
This file contains the relative positon of the fibre in regard of the exit-pupil pupil plane. We have η_{ix} and η_{iy} the position of the fibre end face in the i plane, the point (0,0) is the intersection of this plane with the optic axis. Then we have z_i, the positive distance between the e plane (exit-pupil) and the i plane. Then we have the three coordinates of the unity direction vector of the fiber axis f_{Rx}, f_{Ry} and f_{Rz}. Finally we have R' the radius from the paraxial image point S' and the center of the exit-pupil plane.

Here is an example of file:

```
-11.
6.
20010.
-0.02
+0.03
-1.0
```

2.2.2 DATA_OUT

This directory contains four files. The most important is the one with the results of the coupling efficiency T: *val_coupl_eff.out*. There are two values one, $T_{\%}$, is expressed in percentage of the incoming power and the other, $T_{dB} = -10 * \log(T_{\%})$, is expressed in decibels. The two values are on the same to permit th possibility to have a list of values for differents configurations.

Here is an example of file:

```
55.9548 -2.52163
```

The two following files contains parameters that was read or computed by the program. Text was added to simplify the checking by the user and because there is no input with the code.

Here is an example of file *read_params.out*:

```
Light and surrounding medium caracteristics
lambda_0 = 1.3
n_medium = 1

Intrinsic parameters of the fibre
n_core = 1.46
n_clad = 1.457
d_core = 10
d_clad = 100
fiber_type = 0

Relative positions parameters between the receiving fibre and the exit-pupil plane
eta_i[0]  = -11
eta_i[1]  = 6
z_i  = 20010
fr[0]  = -0.02
fr[1]  = 0.03
fr[2]  = -1

Position of the source image point
eta_p[0] = -10
eta_p[1] = 5
z_p = 20000

Exit pupil window parameters and size of the incoming beam
bound_x.num  = 32
bound_y.num  = 32
bound_x.min = -5500
bound_x.max = 5500
bound_y.min = -5500
bound_y.max = 5500
h_p_sx = 2500
```

```
h_p_sy = 1600
X_OS_p[0] = -300
X_OS_p[1] = 500
```

and of the file *computed_params.out*:

```
Computed parameters

V = 2.26066
w0 = 5.73942
zR = 79.6053
Ri2 = 4.004e+08
R_i = 20010
R_p = 20010
h_p_rx = 1442.7
h_p_ry = 1442.7
X_OR_p[0] = -410.94
X_OR_p[1] = 605.91
centreS[0] = -300
centreS[1] = 500
fr normalized:
fr[0]  = -0.019987
fr[1]  = 0.0299805
fr[2]  = -0.999351
delta_R_p = 10.0008
sind_theta_x = -0.019987
sind_theta_y = 0.0299805
delta_x = -0.995002
delta_y = 0.997501
delta_R_p = 10.0008
centreR[0] = -410.94
centreR[1] = 605.91
k = 4.83322
W_1x =-4.97252e-05
W_1y =4.98501e-05
W_20 =1.24885e-08
warning = 0
The total power of psy_p_S is 0.999983
After have taken into account of the angular fibre misalignment
centreR[0] =-810.88
centreR[1] =1205.82
The total power of psy_p_R is 1
```

The last file *field_exit_pup.out* contains the complex field distributions use for the computation of the overlap-integral (total aberration, source and mode pattern of the fibre) are in ASCII format. Each line of the file contains 8 values the first two are respextively the x and y coordinates in the real dimensions. Then we havesuccesivly the real and imaginary part of the total aberration W_{tot}, of the field distribution of the source Ψ'_S and finally of the field distribution of the mode pattern of the receiving fibre Ψ'_R. You can see visualization of the real part of these distributions in the figures 2.1, 2.2.

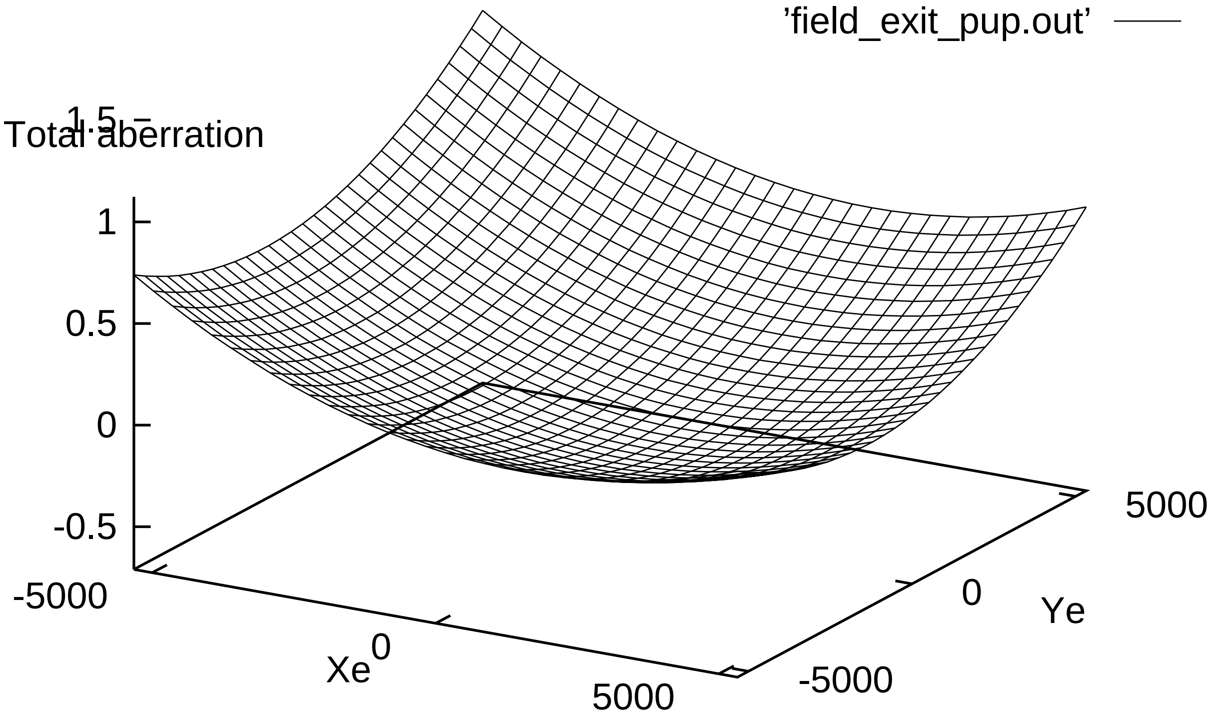


Figure 2.1: Real part of the total aberration W_{tot} of the example.

2.3 How to use the code?

Fill in all the input files with your data the *DATA_IN* directory. Use always the same length unity for all parameters for reliability for example the $\mu metre$. You can use your prefered text editor to edit and write in the files as they are ASCII files. Go to the SRC directory and type "Coupling". Results will appear on the screen and in the file efficiency.out in the *DATA_OUT* directory. If there is no executable, type "make" when you are in the *SRC* directory. It will create a library that contains all functions: *libcplx.a*, an object file *coupling.o* and the executable *Coupling*.

Here is the screen that appears when using the previous input files:

```
*****************************************************************
This program compute the coupling efficiency of optics into
a single-mode fibre

Input data are in the files of the directory DATA_IN, report to
the manual for more precisions
```

```
 The total power of psy_p_S is 0.999983
 The total power of psy_p_R is 1

The computation are finished. You can see results in the directory
DATA_OUT. The coupling efficiency in % and in dB is in the file
val_coupl_eff.out
You can check input data in the file read_params.out
Computed parameters areavailable in the file computed_params.out
Finally complex field distributions use for the computation of the
overlap-integral (total aberration, source and mode pattern of
 the fibre) are in ASCII format in the file field_exit_pup.out

The coupling efficiency for your configuration is:
                     C = -2.52163 dB.

******************************************************************
```

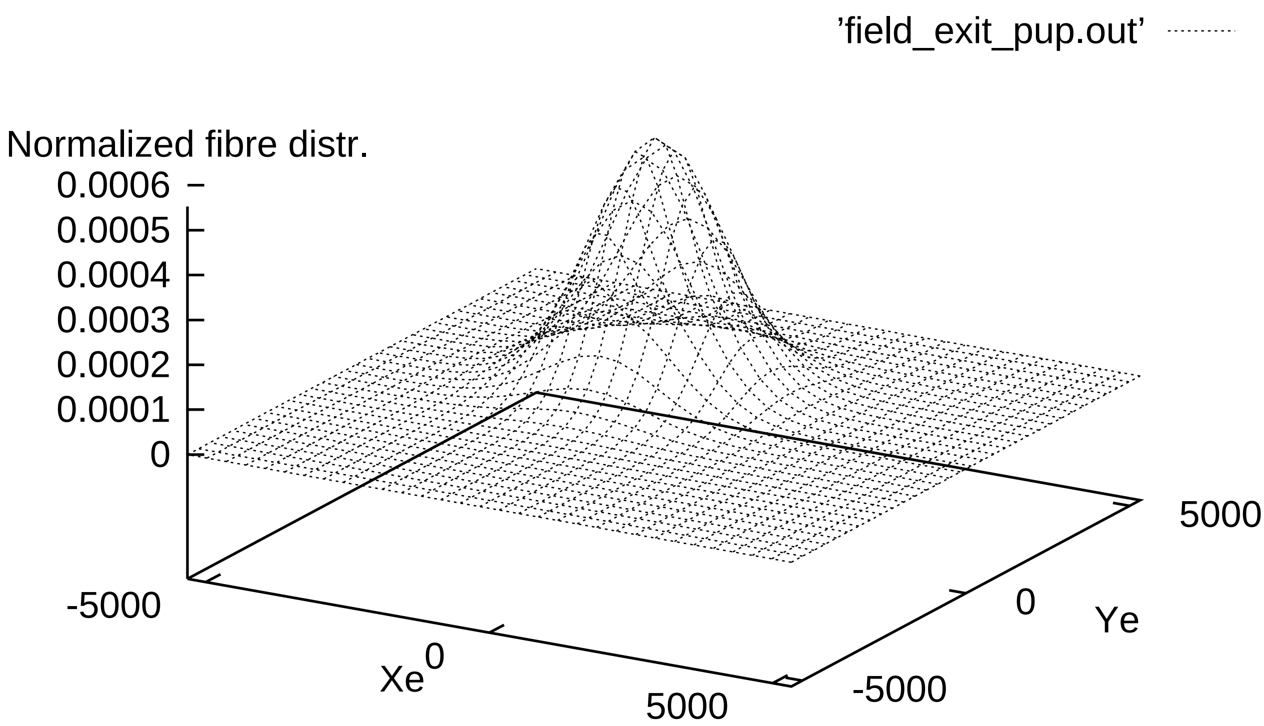
2.3.1 Standard output: warning and error messages

When executed, the program write in the standard output a message to inform that the code is running. It gives warning if needed and finaly the coupling efficiency in dB. For more details, the user can consult the outpout files.

a) Warning messages
   If the window of the exit-pupil is to small i.e. a rectangle with 3 times the sizes of the beams centered on it can't stand in the window, there is a warning message that tells to be careful with the result that may be precise. It is only a warning that is correct when dealing with Gaussian beam. In fact the real the cruxial point is that the distribution must be normalized on the domain where the overlap integration is done. Theorically a Gaussian beam is not limited but in practice, To help the user, the message precise which beam is involved.

```
*************** WARNING MESSAGE *******************
 Result may be not very numerically precise due to
 the size of the INCOMING BEAM compared with the
 window size.
 Please check the differents values of Exit pupil
 window parameters in the file read_params.out.
***************************************************
```

b) I/O files problems
   If there is a problem with opening X-file, there is a message of the type "Problem cannot open file X".



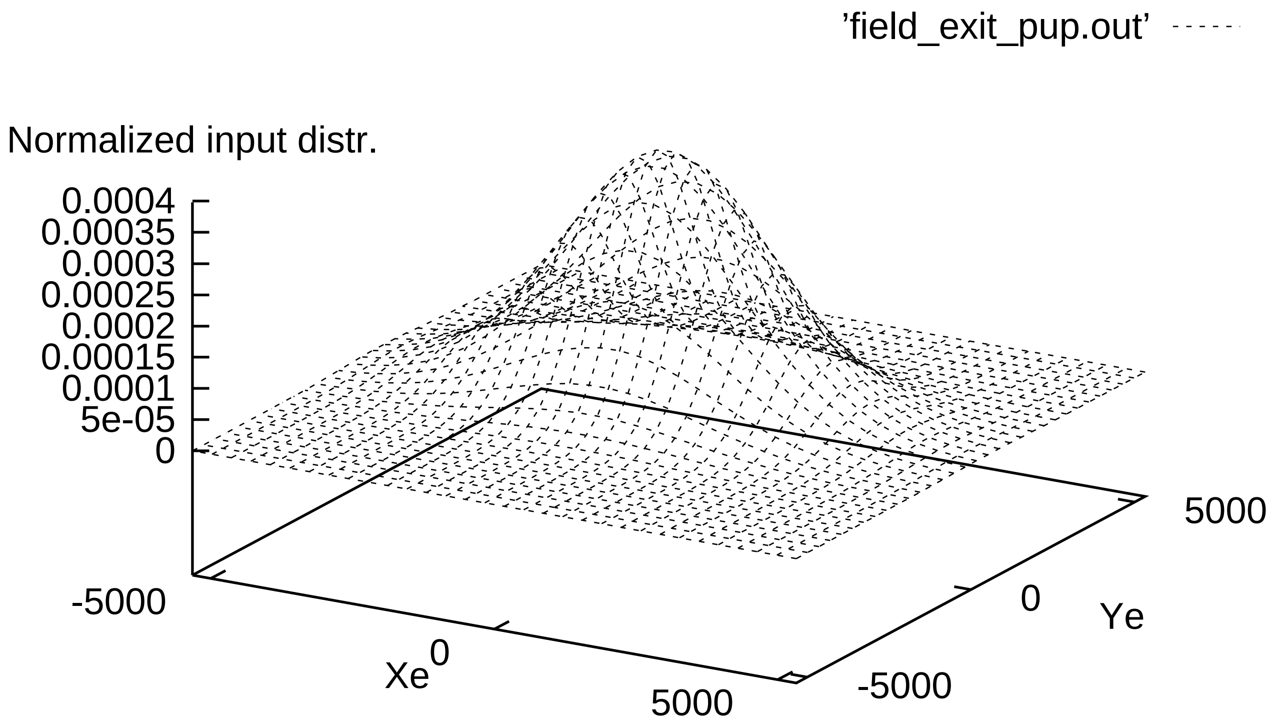


Figure 2.2: Up: real part of the distribution field of the source of the example. Down: real part of the distribution field of the fiber pattern.
The distribution is situated in the exit-pupil plane.

Chapter 3

Annexe

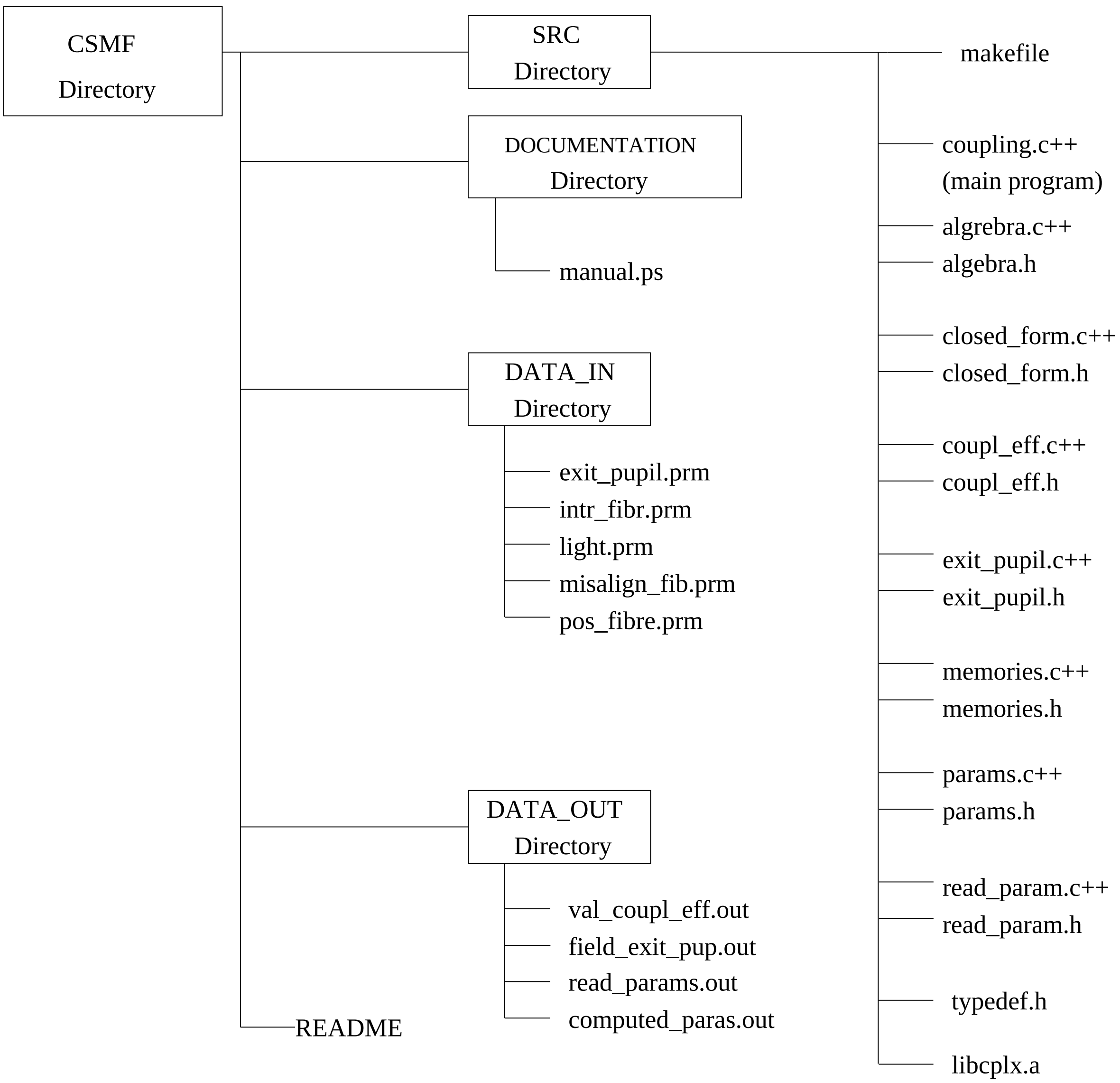


Figure 3.1: Directories architecture of the archive

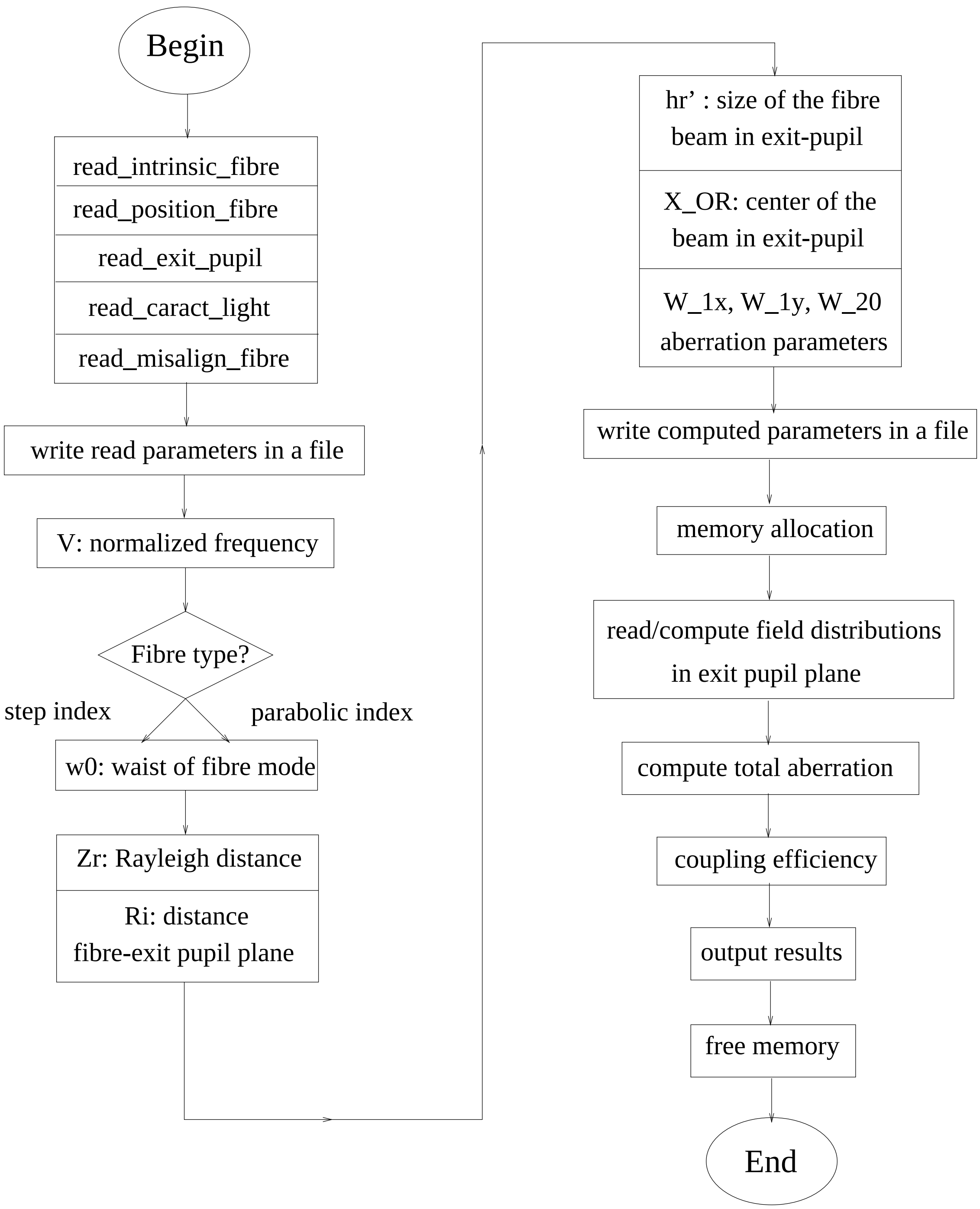


Figure 3.2: Main program organigram

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[1] D. Marcuse. Loss analysis of single-mode fiber splices. *The Bell System Technical Journal*, 56(5), May-june 1977.

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[3] R. E. Wagner and W. J. Tomlison. Coupling efficiency of optics in single-mode fiber components. *Applied Optics*, 21(15), August 1982.