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The Impact of Key Parameters on the Coupling Efficiency of a Linear Transition Between an Optical Fiber and a Waveguide for Telecommunications Networks

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This study focuses on the optimization of a lateral transition that is designed for coupling an optical fiber and a waveguide. The objective is to study the impact of the key parameters of this linear transition on the coupling efficiency, taking into consideration the index variations, the length, and the transition form, in order to improve the transmission performance without losses between the optic fiber and the waveguide. We accomplish this using BeamProb of Rsoft CAD, which relies on the Beam Propagation Method BPM. Besides, we carried out simulations of different shapes and lengths of the lateral transition. The findings of the simulations allowed for the analysis and evaluation of the different configurations of the lateral transition. In order to use this type of transition in the field of optic communications, we examined how the diverse intensities varied in the outlet and inlet of the taper. In addition, the results allow determining the suitable length and form of the taper where the signal is most exploitable.

Keywords: Transition, Coupling, Beam Prob, Taper.

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1. INTRODUCTION

The integration of different optic components is necessary for the development of the communication systems that rely on the optic fibers, such as the switches, the couplers, the multiplexors, the demultiplexers, and the fibers [1-6]. Besides, the harmonious integration of these different optic components associated with an effective coupling between the optic fibers and the waveguide paves the way for important developments in the field of optic fiber communications. This makes the optic networks more performing, more reliable, and more evolutionary, and it meets the increasing needs of data transfer worldwide.

Nevertheless, the implementation of the fiber optic and waveguide coupling is not easy due to the different sizes that cause very high losses; i.e., the transmission is not direct between them. The current solution is to use the transition between the fiber and the waveguide [7-9].

The transition, or taper, is a particular form that aims at linking an optic fiber that guides the light through the central axis towards a waveguide that guides the light through a flat structure. The tapers are used in the photonic devices, the integrated optic circuits, antennas, and the optic sensors to improve the efficiency of the coupling and reduce the reflections or energy losses, allowing a better transmission of the light and the optic signals [10-16].

The study and optimization of a lateral transition between the optic fiber and the waveguide may be carried out to improve the efficiency of coupling the light between the two devices. Many alternatives have been suggested to improve the transition [17-20]. However, we must have a very long transition length and, thus, a structure size that is not compatible with the integrated optics.

The aim of this study is to optimize the linear transition between the optic fiber and the waveguide using a global approach that takes into consideration the geometric parameters, the material properties, and the transition length, form, and alignment. An in-depth understanding of these parameters and of their interactions allows designing more performing coupling devices and paves the way for new advancements in the optic communications and photonic systems.

To reach the objectives, we made a linear transition simulation with BeamProp of Rsoft that is based on the BPM method.

In the 1st section, the paper provides a short introduction about the fiber and the waveguide. Then in the second, we treat the transition structure and BPM method of the used software. The simulation results and the discussion are given in section 3 where we shed light on the analysis of the impact of the different key parameters on the coupling. Finally, we give the conclusion in the fourth section.

2. PRESENTATION OF THE TRANSITION STRUCTURE AND THE PBM METHOD

2.1 The Structure of the Transition

In optics, a taper (also called transition in French) refers to an area where the geometry of a waveguide or optical fiber is gradually changing in shape or dimension. This means that the waveguide or optical fiber is gradually moving from a wider section to a narrower section (tapering down) or vice versa (tapering up).

Fig. 1 illustrates the structure of a transition (taper), which is characterized by a length Ltaper, a height h, and an index difference Δn.

A linear taper is defined by the following function:

$$f(z) = z, \qquad (2.1)$$

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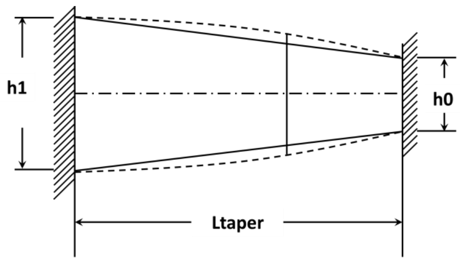


Fig. 1 – Design of the transition (taper)

The height of the type varies according to the z position along the transition:

$$h(z) = h_0 + (h_1 - h_0)\, f(z), \tag{2.2}$$

h_0 and h_1 are the heights at the beginning and end of the guiding structure (optical fiber- waveguide).

The index difference varies with the z position along the transition as a function of $f(z)$.

It is defined as:

$$\Delta n(z) = \Delta n_0 + (\Delta n_1 - \Delta n_0)\, f(z), \tag{2.3}$$

Δn_0 et Δn_1 are the index differences of the beginnings and end of the guiding structure (optic fiber, wavaguide).

Fig. 2 shows the form of the taper used under the graphical interface of R$_{soft}$.

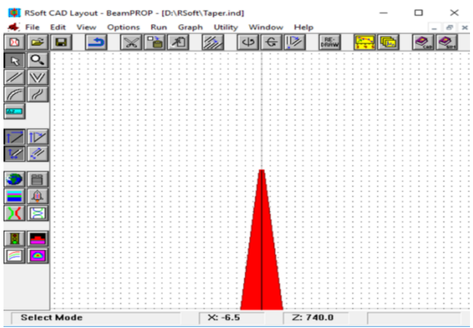


Fig. 2 – Linear Lateral Taper Shape under R$_{soft}$ software

2.2 The BPM Method

The R$_{soft}$ software contains a complete system to design, simulate, and analyze the parameters of the different optical components. Beam.Prob is the integrated module with R$_{soft}$; it is based on the BPM method (Beam Propagation Method).

It is a tool for simulating optical propagation in two- and three-dimensional waveguides. At the heart of the BeamProb is an extremely robust computational program capable of finding the rigorous solutions of Maxwell wave equations, solutions that are completely vector-based and completely bidirectional, taking into account all reflections at the joints at the interface of the different components of the device, because the bidirectional algorithm models all internal reflections [17].

3. SIMULATION ANALYSIS OF THE INFLUENCE OF KEY PARAMETERS ON COUPLING EFFICIENCY.

3.1 Simulation of the Components Related to the Transition

The simulation components are a single-mode fiber (SMF) and a single mode RIB waveguide. The aim is to make a coupling between these two systems using a lateral taper of a linear type.

In this study, the simulation of the propagation modes of the RIB waveguide and the optical fiber is carried out using the Beam.PROB simulator.

As for the optical fiber, we used a Single Mode Fiber SMF in a step-index single mode silica with a diameter of 10 μm whose core refractive index is $n_c = 1.44904$, cladding refractive index is $n_g = 1.44404$, and the index difference is ($\Delta n = 0.005$).

Fig. 3 shows the propagation of the light in the core of the optical fiber following the propagation direction (Z).

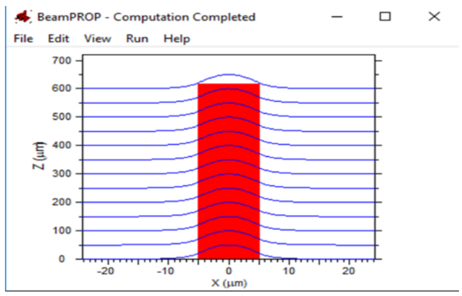


Fig. 3 – Light propagation in SMF fiber

We notice that the light propagates only in the core of the 10 μm optical fiber, and this is according to the direction of propagation (Z)

The structure of the simulated RIB waveguide is shown in Fig. 4, and Table 1 summarizes the fixed parameters and those entered in the dialogue box of the R$_{soft}$ software.

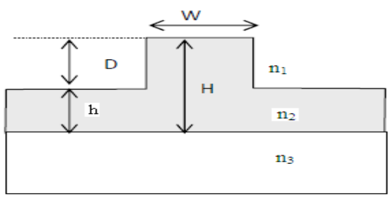


Fig.4– Structure of a RIB waveguide

Table 1 – Optical and geometric parameters of the RIB waveguide used in simulation

Wavelength (λ)	1.55 μm
Background index (n_3)	3.34
Height of the waveguide (H)	1.5 μm
Width of the waveguide (W)	1.1 μm
Height of the slab (h)	0.6 μm
Cover index (n_1)	1
Silica index (n_2)	1.4404
The depth of the engraving (D)	0.9 μm

An optimization of the parameters of the RIB waveguide showed its insensitivity to the polarization [16]. Fig. 5 shows the results of the simulation obtained from the intensity of the field for the two types of polarization, TE and TM.

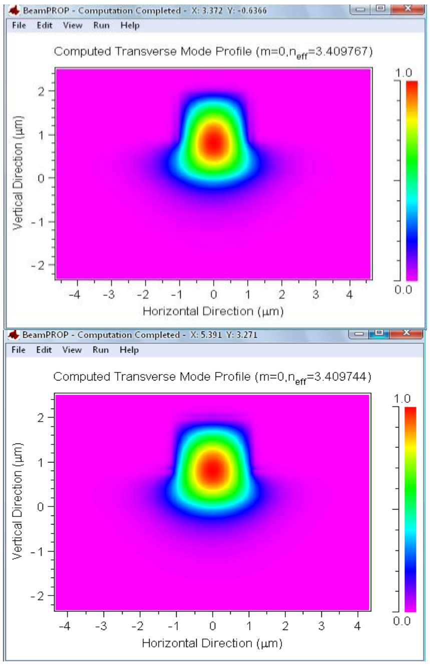


Fig. 5 – Field strength containment in the RIB guide for both TE and TM polarizations respectively

The fibers and the waveguides support different propagation modes. An efficient transformation must facilitate the conversion of the fiber modes into appropriate modes of the waveguide.

3.2 Influence of Key Transition Parameters on Coupling Efficiency

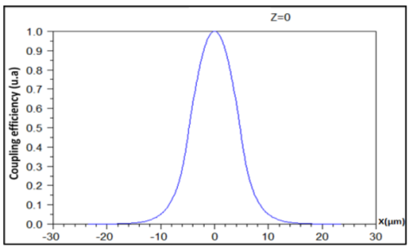
We study the influence of the key transition parameters on the efficiency of the coupling in order to find the optimal characteristics of the transition (taper) that allow coupling the fiber and the waveguide, i.e., a propagation without losing the optical capacity at a telecommunication wave length $\lambda = 1.55$ µm.

Simulation analysis of the transition or taper was performed with a 2D beam propagation method (BPM).

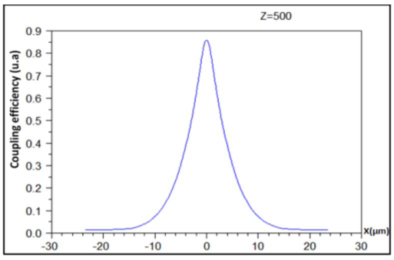
We show the results of the obtained simulation in Table 2 for many values of the index difference, and for a fixed length of the transition, $L_{taper} = 500$ µm.

Fig. 6.a shows the profile of the field at the start of the transition where a capacity of 100 % is sent. On the other hand, Fig. 6.b shows the profile of the field at the end of the transition, i.e., what is really coupled in the waveguide.

For $L = 500$ µm, the capacity sent to the outlet of the transition is around 87 %. Thus, we get a coupling efficiency that is close to 87.36 %, i.e., 12.64 % of losses.



(a)



(b)

Fig. 6 – The profile of the field at the beginning of the transition (a); at the end of the transition (b)

Table 2 – Results of the coupling efficiency and the losses according to index difference transition

Index difference Δn	Coupling efficiency (%)	The losses (%)
0.003	77.39	22.61
0.004	82.27	17.73
0.005	87.36	12.64
0.006	92.33	7.67
0.007	95	5

We notice in Table 2 that the losses reduce when Δn increases. Therefore, we can deduce that the value of the index difference ($\Delta n = 0.007$) is optimal because it guarantees better confinement of the light. Consequently, if we increase the index difference of the fiber, the coupling efficiency increases.

3.3 The Influence of the Transition Length

In order to study the influence of the transition length, we change the Ltaper value each time from 500 to 900 µm and, then, measure the coupling efficiency. We kept all the other fixed parameters and the index difference optimum ($\Delta n = 0.007$). Table 3 summarizes all the results.

Table 3 – Results of the coupling efficiency and the losses according to the transition length

LTaper (µm)	Coupling efficiency (%)	The losses (%)
500	95	5
600	89	11
700	80	20
800	75	25
900	67	33

In this transition case, and for a length of 500 µm, a transmission coefficient of approximately 95 % of the input power is observed, with only a 5 % loss of light; this is a significant improvement compared to [17,20].

The different simulated transition lengths should be chosen neither too short in order to limit light leakage, nor too long due to space constraints.

3.4 The Influence of the Transition Form (Shape)

In this section, the obtained results of various profiles of the taper used during the simulation are presented, with their corresponding mathematical functions being of the exponential and quadrature types. The coupling efficiency and the corresponding losses for the taper shapes are reported in Table 4, while keeping the transition length at 500 μm and $\Delta n = 0.007$.

Table 4 – Results of the coupling efficiency and the losses according to the transition form

Transition form	Coupling efficiency (%)	The losses in (dB)
Linear	87%	11.13
exponential	76%	13.80
quadratic	70%	14.77

We notice that the transformation shape influences the exit characteristics, mainly the coupling efficiency and, thus, the losses.

Besides, we notice that the linear shape gives the minimum losses compared to the exponential and quadrature profiles.

The choice of the transformation shape depends on the material's properties, the length of the work wave, and the length of the transition.

4. CONCLUSIONS

Through this study, we managed to show that the efficiency of coupling a linear transition between an optic fiber and a waveguide is directly influenced by many key parameters. Our analysis proved that these parameters play a crucial role in the optic energy transfer between the two devices and that their optimization is necessary to improve the performance of the transmission system.

The geometry and profile of the optic fiber and waveguide mode must be carefully taken into consideration. A precise adaptation of these profiles allows for minimizing the energy losses and getting a more efficient coupling.

The transmission length and form are critical parameters. The simplest form gives efficiency rates of 87 % and a length of 500 μm, while the exponential form allows for a coupling efficiency of 76 % and lengths between 600 and 650 μm. For the quadratic form, an efficiency rate of 70 % has been retained for 650 μm in length.

Besides, the properties of the materials used for the fabrication of the coupling dispositive may play a major role. Their refraction index, their transparency at the wavelength of interest, and their intrinsic optic losses may significantly affect the coupling efficiency.

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Вплив ключових параметрів на ефективність зв’язку лінійного переходу між оптичним волокном і хвилеводом для телекомунікаційних мереж

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Дослідження було зосереджено на оптимізації бокового переходу, призначеного для з’єднання оптичного волокна та хвилеводу. Мета полягає в тому, щоб вивчити вплив ключових параметрів цього лінійного переходу на ефективність зв’язку, беручи до уваги варіації індексу, довжину та форму переходу, щоб покращити продуктивність передачі без втрат між оптичним волокном і хвилевід. Ми досягаємо цього за допомогою BeamProb із Rsoft CAD, який спирається на метод поширення променя BPM. Крім того, ми провели моделювання різних форм і довжин бічного переходу. Результати моделювання дозволили провести аналіз та оцінку різних конфігурацій бічного переходу. Для того, щоб використовувати цей тип переходу в області оптичних комунікацій, необхідно провести перевірку того, яким чином різні інтенсивності змінюються на виході та вході звуження. Крім того, результати дозволяють визначити відповідну довжину та форму конусності, де сигнал найбільш придатний для використання.

Ключові слова: Зчеплення, Балка, Конусність.