Mode-Selective Couplers for Two-Mode Transmission at 850 nm in Standard SMF

Juan L. Corral, David Garcia-Rodriguez, and Roberto Llorente

Abstract—The optimal design of a low loss fused fiber mode selective coupler for two-mode fiber transmission in the 850 nm band is presented. The coupler is based on precise phase matching the propagation constants in each arm of a weakly fused fiber coupler. The designed component permits both mode converter and mode multiplexer/demultiplexer operation, thus enabling modal multiplexing transmission in this band with no additional component.

The presented design is evaluated by simulation considering two type of structures, leading to asymmetric and symmetric coupler configurations. Mode converter and mode multiplexer operation is achieved with 93.5% efficiency in the band of 845 to 855 nm. Mode demultiplexer operation is achieved with an extinction ratio better than 20.4 dB in the same band.

Index Terms—Few-mode fiber, Mode converter, Mode Multiplexer, Optical fiber coupler, Space division multiplexing.

I. INTRODUCTION

RECENTLY, significant research efforts have been directed to increase the capacity of fiber optic communication networks by adding spatial division multiplexing or mode division multiplexing (MDM) to current technology [1]. Mode converters and mode multiplexers/demultiplexers are key components in a MDM system to combine and split the different modulated optical signals.

Mode couplers based on free space have been successfully used in MDM experiments [2] but the devices based on directional couplers (DC) offer a more compact and cheap solution, with less losses and with direct integration with optical fiber. Recently, the use of a fiber based directional coupler for a MDM system at 1550 nm has been theoretically [3] and experimentally [4, 5] considered. However, the proposed system is based on the use of a specialty fiber with a two-mode behavior at 1550 nm. Thus, the huge amount of standard single-mode fiber already deployed could not be used. Instead, standard single-mode fiber (SSMF) can be used as a two-mode fiber (TMF) if short wavelengths below cutoff wavelength are chosen.

For instance, a fiber directional coupler has been reported as a mode coupler at 1080 nm in a MDM link based on SSMF but an additional fiber grating was required to convert modes [6]. We propose to use the band around 850 nm where low cost VCSELs are available with modulation bandwidth beyond 10 Gb/s. This band is widely used for short range high data rate optical links with multimode fiber (MMF). The use of a fiber bundle composed of 4 or 10 parallel multimode fibers is already standardized as a way to multiply link capacity in the 850 nm band [7] but the use of MDM would be a more efficient way to increase the data rate capacity of a single fiber.

The use of SSMF at the 850 nm band has been proposed by including mode filters to avoid the higher order modes but without taking profit of the capacity increase available if MDM were used [8, 9]. The availability of low cost devices to convert, multiplex and demultiplex spatial modes in the 850 nm band on SSMF could ease the development of this multiplexing technique.

In this paper, the use of directional couplers as mode selective couplers for SSMF at 850 nm is analyzed and optimal designs in terms of coupling efficiencies and extinction ratios are obtained. The organization of this paper is as follows: in Section II the coupler model is described, Section III presents the optimal design of an asymmetric coupler working as mode converter and mode multiplexer/demultiplexer whereas Section IV is devoted to a symmetric coupler working as a mode multiplexer/demultiplexer. Finally, some remarks and conclusions are summarized in Section V.

II. MODEL

A. System

The basic concept of the MDM link is depicted in Fig. 1. It consists of two lasers emitting at a wavelength (e.g. 850 nm) below the SSMF cutoff wavelength. In this configuration, the SSMF behaves effectively as a two-mode fiber (TMF). The optical signals coming from the lasers will correspond to the LP01 mode if the lasers are properly aligned to the fiber centers or if the pigtails are made of fiber operating as single mode at 850 nm [9]. A mode converter (LP01 to LP11) and a mode multiplexer are needed at the transmitter in order to transfer the...
modulated optical carriers coming from both lasers to the LP\textsubscript{01} and LP\textsubscript{11} modes in the SMF. At the receiver side, a mode demultiplexer will be needed to direct each mode to the corresponding photodiode; however, the mode conversion (LP\textsubscript{11} in the SMF to LP\textsubscript{01} impinging photodiode PD2) is not strictly needed if the fiber connecting the mode demultiplexer to the PD2 photodiode is also SMF.

### B. Mode Selective Couplers

We propose the use of fiber based directional couplers as mode converter, mode multiplexer and mode demultiplexer in a MDM system, as depicted in Fig. 1. The waveguide structure of a fiber based mode coupler is shown in figure 2. This coupler is realized by weakly fusing two similar (symmetric coupler) or dissimilar (asymmetric coupler) fibers together. The principle of the asymmetric coupler is to phase match the fundamental mode in one fiber to a high order mode in a TMF in order to achieve a conversion to the high order mode. In a symmetric coupler, no mode conversion is obtained but the signal is coupled from one fiber to the other depending on the coupler function of the input power,

\[ P_A(L) = P_A(0) \left( \frac{\kappa_{ab} \kappa_{ba}}{\beta_b} \right) \cos^2 \left( \beta_c L \right) + \left( \frac{\delta}{\beta_c} \right)^2 \]

\[ P_B(L) = P_A(0) \left( \frac{\kappa_{ab}^2}{\beta_c^2} \right) \sin^2 \left( \beta_c L \right) \]

\[ \delta = \frac{\left( \beta_c + \kappa_{ba} \right) - \left( \beta_c + \kappa_{ab} \right)}{2} \]

\[ \beta_c = \sqrt{\kappa_{ab} \kappa_{ba} + \delta^2} \]

where \( \kappa_{ab}, \kappa_{ba}, \kappa_{ob}, \) and \( \kappa_{ob} \) are the self-coupling and mutual coupling coefficients, respectively, and \( \delta \) is the phase mismatch term which plays an important role in the coupling efficiency of the coupler. Finally, the coupling efficiency is defined as:

\[ \eta = \frac{P_B(L)}{P_A(0)} = \frac{\kappa_{ab}^2}{\beta_c^2} \sin^2 \left( \beta_c L \right) \]

It is clear from (1) and (2) that maximum power coupling from fiber A to fiber B will require the phase mismatch, \( \delta \), to be zero. In this case, the maximum coupling efficiency will be achieved when \( \sin(\beta_c L) = 1 \). When the phase-match condition is fulfilled, \( \beta_c \) depends on the mutual coupling coefficients which depend on the fiber separation, \( d \), and the spatial modes profiles to be coupled.

When the coupler is made of similar fibers (symmetric coupler) the phase-match condition is always fulfilled if the modes to be coupled are the same one \((a=b)\). However, in an asymmetric coupler the effective indexes of the modes to be coupled must be matched by properly selecting the features of the respective fibers to be used. The easiest way to adapt the fiber parameters is to pre-taper one of the fibers during the coupler fabrication in order to reduce its core diameter [4].

Once the effective indexes of the modes to be coupled are matched and the fibers spacing is fixed, the mutual couplings coefficients are known (they will be higher for closer fibers) and the maximum coupling efficiency will be obtained for different coupling lengths according to (5).

### C. Fiber

The fiber to be used for the couplers and the optical link will be standard single-mode fiber; namely, SMF-28 from Corning Inc. (8.2 \( \mu \)m core diameter, \( \Delta = 0.36\% \) refractive index difference and a SiO\textsubscript{2} cladding). This fiber will behave as a two mode fiber at 850 nm propagating the LP\textsubscript{01} and LP\textsubscript{11} (including odd and even degenerated versions) linear polarization modes. A full vectorial Beam Propagation Method has been used to compute the modal effective index and to simulate the different mode selective couplers. The calculated refractive indexes for the SMF-28 fiber at 850 nm are \( n_{\text{core}}=1.4557 \), \( n_{\text{cladding}}=1.4525 \), \( n_{\text{core}}^{\text{SMF}}=1.4564 \) and \( n_{\text{LP11}}^{\text{SMF}}=1.4545 \). The relative difference between both modes indexes (0.13 \%) will assure that no modal coupling will appear along the SMF link as the measurements in [8] confirmed.

### III. ASYMMETRIC COUPLER

The asymmetric coupler is made of a single-mode fiber (SMF) propagating only the fundamental mode and a two-mode fiber propagating both LP\textsubscript{01} and LP\textsubscript{11} modes. In this case, the LP\textsubscript{01} mode entering the coupler through the SMF must be converted to LP\textsubscript{11} at the TMF output of the coupler. Thus, the effective index of LP\textsubscript{01} in SMF must match the LP\textsubscript{11} index in TMF which can be accomplished by reducing the core diameter of a SMF-28 fiber to 4.17 \( \mu \)m. This reduction of SMF-28 core...
important parameters are the coupling efficiency from the LP01 input in the SMF to the LP11 output in the TMF and the insertion index as the LP11 mode in TMF as depicted in Fig. 3. Now, the phase match condition is fulfilled and the maximum coupling efficiency from LP01 in SMF to LP11 in TMF can be obtained. This asymmetric coupler has been simulated at 850 nm for different values of fiber separation, \( d \) (\( \mu m \)) and coupling length, \( L \) (mm) and the results are shown in Fig. 4. As expected, for a fixed fiber separation, different coupling lengths achieve the maximum coupling efficiency according to the sinusoidal expression in (5). For wider fiber separations, the mutual coupling coefficients are reduced and the coupler requires longer lengths to achieve the maximum efficiency.

Different combinations of fiber separation and coupler length offering the maximum coupling efficiency can be selected from Fig. 4. In order to compare some of the combinations, the performance of the coupler has been assessed, both for the design wavelength of 850 nm and for different wavelengths around 850 nm. The results are shown in Fig. 5 for the four cases: \((d=6 \mu m, L_1=15.66 \, mm)\), \((d=6 \mu m, L_2=46.95 \, mm)\), \((d=7 \mu m, L=28.56 \, mm)\) and \((d=8 \mu m, L=52.17 \, mm)\) highlighted in Fig. 4.

When the asymmetric coupler is used as a mode converter and multiplexer as in the transmitter in Fig. 1, the most important parameters are the coupling efficiency from the LP01 input in the SMF to the LP11 output in the TMF and the insertion losses for the LP01 mode from input to output of the TMF. The insertion losses for the LP01 mode in the TMF are negligible as this mode is not coupled to the SMF and the length of the fiber is too short to introduce any significant loss. The coupling efficiency for this case is shown in Fig. 5 where all four cases offer an efficiency better than 99% (coupling losses below 0.05 dB) at the design wavelength. However, the performance of the coupler for a broader bandwidth is quite dependent on the fiber spacing of the coupler and the best coupling efficiency is obtained for the lower spacing and the shorter coupling length \((d=6 \mu m, L_1=15.66 \, mm)\) with a 93.5% (corresponding to a 0.3 dB insertion loss) coupling efficiency for a 10 nm bandwidth around 850 nm.

The asymmetric coupler could be used in the receiver side of the link as a mode converter and demultiplexer. In this case, both LP01 and LP11 modes enter the coupler through the TMF input and they are split into the TMF (LP01) and the SMF (LP11) outputs. The most important parameters to check besides the ones already considered in the multiplexer will be the extinction ratio of the LP11 mode at the TMF output and the undesired leakage of the LP01 mode from the TMF to the SMF. These parameters are plotted in Fig. 5 where values above 34 dB are observed at 850 nm. However, when a 10 nm bandwidth is considered the LP11 extinction ratio is quite reduced with the best performance obtained again for the coupler with the lower spacing and the shorter coupling length with an extinction ratio above 11.6 dB and a leakage above 33.6 dB.

The asymmetric coupler shows an outstanding performance as mode converter and multiplexer but its performance as mode demultiplexer would be limited by the sensitivity of the LP11 extinction ratio to deviations of the laser wavelength. This limitation in its use as mode demultiplexer can be easily avoided by adding a modal filter after the TMF output of the coupler. The easiest implementation of this modal filter is to add some thigh turns to the fiber coming out of the TMF output of the coupler as more than 20 dB attenuation has been reported for 30 turns around a cylinder of 9-mm radius [8].

Concerning the demultiplexer, it is important to point out that, as it happens with all mode-selective couplers, the LP11 mode entering the coupler must be properly aligned (axial orientation of the mode aligned with the plane containing the fibers of the coupler, horizontal axis in Fig. 2) which can be easily accomplished by adding an inline polarization controller acting as a mode rotator before the demultiplexer [9].

IV. SYMMETRIC COUPLER

Compared with an asymmetric coupler, the propagation constants (thus, the effective refractive indices) of the same modes in the two fibers of a symmetric coupler are always matched at any given wavelength, and thus the device can be broadband. On the other hand, additional mode conversion, like
a long-period fiber Bragg grating (LPFBG), is needed before mode coupling if the symmetric coupler is to be used as multiplexer in the transmitter in Fig. 1 [5, 6].

However, the symmetric coupler can be advantageously used as a mode demultiplexer at the receiver side in the setup shown in Fig. 1 without any additional mode conversion as the LP01 and LP11 spatial modes coming from the fiber link will be split, and each mode LP01 or LP11 will impinge the corresponding photodiode without any mode conversion.

Fig. 6 show the LP11 coupling efficiency of the symmetric coupler at 850 nm for different values of fiber separation, \(d\) (\(\mu m\)) and coupling length, \(L\) (mm). Fig. 7 show the simulation results of the four cases: \((d=6\,\mu m, L=17.01\,mm)\), \((d=6\,\mu m, L=51.09\,mm)\), \((d=7\,\mu m, L=31.14\,mm)\) and \((d=8\,\mu m, L=56.58\,mm)\) highlighted in Fig. 6 corresponding to different designs offering the maximum coupling efficient at 850 nm.

As expected the LP11 coupling efficiency of the symmetric coupler is quite less sensitive to wavelength variation and a coupling efficiency better than 99% (insertion loss below 0.04 dB) can be achieved in a 10 nm bandwidth around 850 nm when the minimum coupling length for any fixed fiber separation is selected. The insertion loss for the LP01 (straight path) in these three cases is better than 0.09 dB in the same bandwidth. Thus, the use of the symmetric coupler as a mode multiplexer in Fig. 1 could be an interesting option if an external mode converter could be easily obtained. In other case, the asymmetric coupler from section III would be a better option.

In order to consider the use of the symmetric coupler as a demultiplexer in the receiver side of Fig. 1, the extinction ratio for both modes in the opposite output of the coupler should be considered. In the symmetric coupler, both modes, LP01 and LP11, are coupled, although the LP01 mode requires quite longer coupling lengths. If the LP01 extinction ratio for both couplers with \(d=6\,\mu m\) are compared (17.5 dB for \(L_1\) and 8.2 dB for \(L_2\) at 850 nm) it is clear that the minimum coupling length must be selected to minimize the undesired coupling of the LP01 mode. The corresponding insertion losses for the LP01 mode in the straight path are also better for shorter couplers (0.08 dB for \(L_1\) and 0.7 dB for \(L_2\) at 850 nm).

The wider the separation between the fibers, the higher the LP01 extinction ratio (17.1 dB, 19 dB, 20.8 dB for \(d=6, 7\) and 8 \(\mu m\) for a 10 nm bandwidth around 850 nm) but the lower the LP11 extinction ratio (22.7 dB, 21.5 dB and 20.4 dB respectively). The \(d=8\,\mu m, L=56.58\,mm\) symmetric coupler offers the best overall performance taking into account that the LP11 can be further attenuated at the corresponding output as previously commented for the asymmetric coupler.

V. CONCLUSION

In this work, we propose the use of mode selective couplers at the band around 850 nm with standard single-mode fiber to achieve modal multiplexing with the LP01 and LP11 modes.

The best overall performance is obtained when an asymmetric coupler \((d=6\,\mu m; L=15.66\,mm)\) is selected as a mode converter and multiplexer (coupling efficiency 93.5%) and a symmetric coupler \((d=8\,\mu m; L=56.58\,mm)\) is used as demultiplexer (extinction ratio <20.4dB) for a 10 nm bandwidth around 850 nm.

REFERENCES


