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Corral, JL.; García Rodríguez, D.; Llorente Sáez, R. (2016). Mode-selective couplers for two-mode transmission at 850 nm in standard SMF. IEEE Photonics Technology Letters. 28(4):425-428. doi:10.1109/LPT.2015.2497080.

The final publication is available at

http://dx.doi.org/10.1109/LPT.2015.2497080

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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.

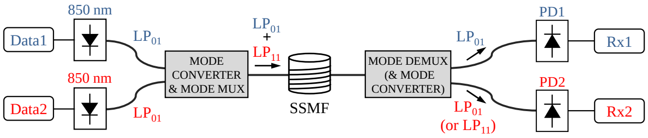

Fig. 1. Scheme for mode-division multiplexing (MDM) at short wavelengths with SSMF as two-mode fiber (TMF) optical transmission media.

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 LP_{01} 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 (LP_{01} to LP_{11}) and a mode multiplexer are needed at the transmitter in order to transfer the

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Manuscript received X; revised X; accepted X. This work was supported by the Spanish Ministerio de Economia y Competitividad under projects TEC2012-38558-C02-01 and RTC-2014-2232-3 HIDRASENSE.

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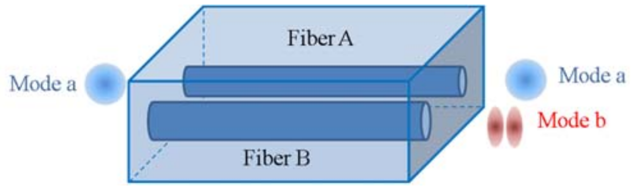

Fig. 2. Waveguide structure of the fiber-based mode coupler.

modulated optical carriers coming from both lasers to the LP_{01} and LP_{11} modes in the SSMF. At the receiver side, a mode demultiplexer will be needed to direct each mode to the corresponding photodiode; however, the mode conversion (LP_{11} in the SSMF to LP_{01} impinging photodiode PD2) is not strictly needed if the fiber connecting the mode demultiplexer to the PD2 photodiode is also SSMF.

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 geometry. The weak fused technique will ensure that the fiber geometries are kept and an accurate index matching is achieved.

According to Fig. 2 the fiber coupler is made of two fibers (A, B) that are fused together with their cores surrounded by the cladding of both fibers and keeping a constant distance, *d*, between them. We are interested in studying the coupling between spatial mode *a* in fiber A (power P_A, propagation constant β_a) and spatial mode *b* in fiber B (power P_B, propagation constant β_b). According to the coupled-mode theory if the only optical signal present at the coupler input is mode *a* at the input of fiber A, the optical power at both outputs (direct and coupled paths) of the coupler of length *L* as a function of the input power, $P_A(0)$, can be expressed as [10]:

$$\frac{P_A(L)}{P_A(0)}=\left(\frac{\kappa_{ab}\kappa_{ba}}{\beta_c^2}\right)\cos^2(\beta_c L)+\left(\frac{\delta}{\beta_c}\right)^2 \tag{1}$$

$$\frac{P_B(L)}{P_A(0)}=\frac{|\kappa_{ba}|^2}{\beta_c^2}\sin^2(\beta_c L) \tag{2}$$

$$\delta=\frac{(\beta_b+\kappa_{bb})-(\beta_a+\kappa_{aa})}{2} \tag{3}$$

$$\beta_c=\sqrt{\kappa_{ab}\kappa_{ba}+\delta^2} \tag{4}$$

where κ_{aa}, κ_{bb}, κ_{ab}, and κ_{ba} are the self-coupling and mutual coupling coefficients, respectively, and δ is the phase mismatch term which plays an important role in the coupling efficiency of the coupler. Finally, the coupling efficiency is defined as:

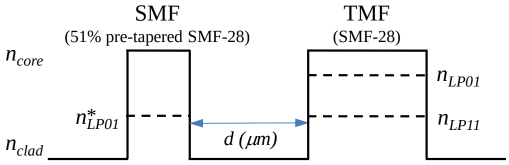

Fig. 3. Refractive index profile of the asymmetric coupler.

$$\eta=\frac{P_B(L)}{P_A(0)}=\frac{|\kappa_{ba}|^2}{\beta_c^2}\sin^2(\beta_c L) \tag{5}$$

It is clear from (1) and (2) that maximum power coupling from fiber A to fiber B will require the phase mismatch, δ, 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, β_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 μm core diameter, $\Delta=0.36\%$ refractive index difference and a SiO_2 cladding). This fiber will behave as a two mode fiber at 850 nm propagating the LP_{01} and LP_{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 $n_{core}=1.4577$, $n_{cladding}=1.4525$, $n_{LP01}=1.4564$ and $n_{LP11}=1.4545$. The relative difference between both modes indexes (0.13 %) will assure that no modal coupling will appear along the SSMF 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_{01} and LP_{11} modes. In this case, the LP_{01} mode entering the coupler through the SMF must be converted to LP_{11} at the TMF output of the coupler. Thus, the effective index of LP_{01} in SMF must match the LP_{11} index in TMF which can be accomplished by reducing the core diameter of a SMF-28 fiber to 4.17 μm. This reduction of SMF-28 core

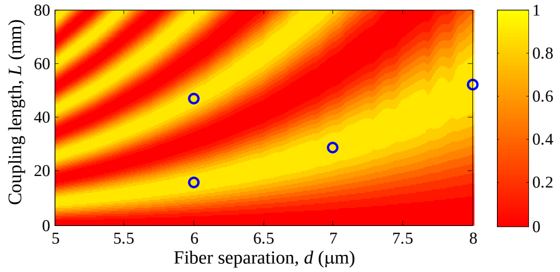

Fig. 4. $LP_{01} \rightarrow LP_{11}$ coupling efficiency for an asymmetric mode-selective coupler with the refractive index profile from Fig. 3.

diameter up to 51% of its original core diameter can be accomplished by pre-tapering the fiber during the fabrication of the coupler [3, 4].

Once the core diameter of the SMF-28 fiber is pre-tapered to 51% of the original core diameter, the fiber becomes single-mode at 850 nm and the effective index of the fundamental mode, LP_{01}, changes to n^*_{LP01}=1.4545, the same index as the LP_{11} mode in TMF as depicted in Fig. 3. Now, the phase match condition is fulfilled and the maximum coupling efficiency from LP_{01} in SMF to LP_{11} in TMF can be obtained. This asymmetric coupler has been simulated at 850 nm for different values of fiber separation, *d* (µm) 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 µm, L_1=15.66 mm), (d=6 µm, L_2=46.95 mm), (d=7 µm, L=28.56 mm) and (d=8 µm, 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 LP_{01} input in the SMF to the LP_{11} output in the TMF and the insertion losses for the LP_{01} mode from input to output of the TMF. The insertion losses for the LP_{01} 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 µm, 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 LP_{01} and LP_{11} modes enter the coupler through the TMF input and they are split into the TMF (LP_{01}) and the SMF (LP_{11}) outputs. The most important parameters to check besides the ones already considered in the multiplexer will be the extinction ratio of the LP_{11} mode at the TMF output and the undesired leakage of the LP_{01} 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 LP_{11} 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.

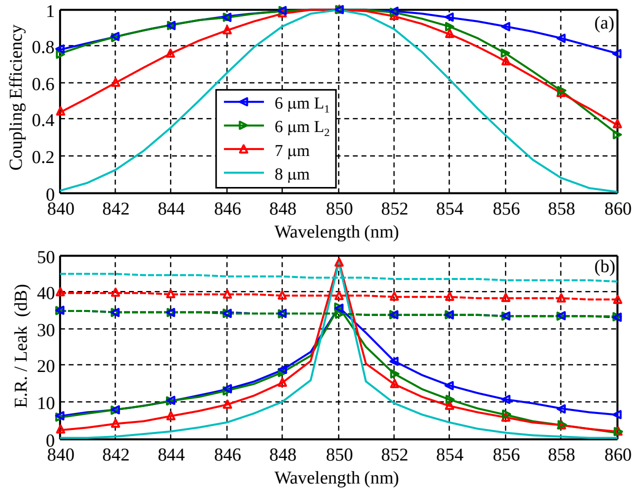

Fig. 5. (a) $LP_{01} \rightarrow LP_{11}$ coupling efficiency, (b) LP_{11} extinction ratio and LP_{01} leakage (dashed line) for the asymmetric coupler from Fig. 3 for different combinations of fiber separation, *d*, and coupler length, *L*.

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 LP_{11} 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 LP_{11} 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

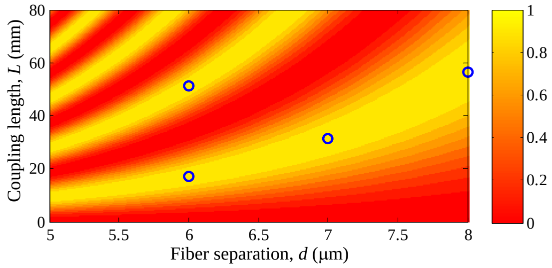

Fig. 6. LP_{11} coupling efficiency for a symmetric mode-selective coupler made of SMF-28 fiber.

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 LP_{01} and LP_{11} spatial modes coming from the fiber link will be split, and each mode LP_{01} or LP_{11} will impinge the corresponding photodiode without any mode conversion.

Fig. 6 show the LP_{11} coupling efficiency of the symmetric coupler at 850 nm for different values of fiber separation, *d* (μm) and coupling length, *L* (mm). Fig. 7 show the simulation results of the four cases: (d=6 μm, L=17.01 mm), (d=6 μm, L=51.09 mm), (d=7 μm, L=31.14 mm) and (d=8 μm, L=56.58 mm) highlighted in Fig. 6 corresponding to different designs offering the maximum coupling efficient at 850 nm.

As expected the LP_{11} 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 LP_{01} (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, LP_{01} and LP_{11}, are coupled, although the LP_{01} mode requires quite longer coupling lengths. If the LP_{01} extinction ratio for both couplers with d=6 μm 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 LP_{01} mode. The corresponding insertion losses for the LP_{01} 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 LP_{01} extinction ratio (17.1 dB, 19 dB, 20.8 dB for d=6, 7 and 8 μm for a 10 nm bandwidth around 850 nm) but the lower the LP_{11} extinction ratio (22.7 dB, 21.5 dB and 20.4 dB respectively). The d=8 μm, L=56.58 mm symmetric coupler offers the best overall performance taking into account that the LP_{11} can be further attenuated at the corresponding output as previously commented for the asymmetric coupler.

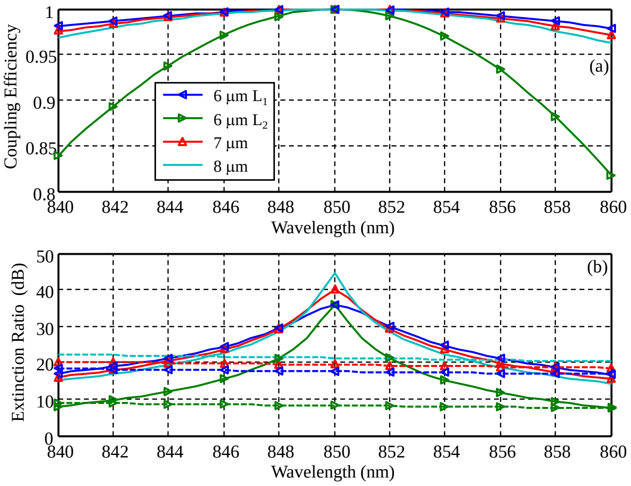

Fig. 7. (a) LP_{11} coupling efficiency, (b) LP_{11} and LP_{01} (dashed line) extinction ratios for the symmetric coupler for different combinations of fiber separation, *d*, and coupler length, *L*.

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 LP_{01} and LP_{11} modes.

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

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