Modal Selectivity at 850 nm employing Standard Single-Mode Couplers: Theory and Experimental Demonstration

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Abstract

In this paper, we evaluate experimentally and analyze theoretically and by simulation the demultiplexing of LP_{01} and LP_{11} modes in a 850 nm few mode optical link when a standard single-mode coupler theoretically designed for 1550 nm operation is used. The simulation analysis indicates a feasible conversion efficiency higher than 98% for the LP_{01} mode and 100% efficiency for LP_{11} mode. These results are experimentally validated considering different off-the-shelf optical couplers configured in 99:1, 90:10, 80:20 and 60:40 coupling ratios. Experimental analysis of the optical couplers demonstrate adequate functionality in correspondence with the theoretical analysis, exhibiting a good near-field pattern and modal profile for the LP_{01} and LP_{11} modes. The mode purity observed was 98.4% for the LP_{01} mode, and higher than 90% for the LP_{11} mode. The 90:10 optical coupler configuration shows best mode purity with the minimal insertion losses.

Key words: Optical fiber coupler, mode multiplexer, mode division multiplexing, few-mode fiber.

1. Introduction

In the last decade, due to the huge amount of internet traffic, researchers have focused their efforts to increase the transmission capacity of the optical systems. Five physical dimensions can be employed to characterize the optical data transmitted (time, wavelength, quadrature, polarization and spatial propagation mode) [1]. Space division multiplexing (SDM) or mode division multiplexing (MDM) are the key to surpass the capacity limit of the optical fiber, either employing multicore fibers or different optical modes in the optical fiber [2-6]. The fibers that support tens of modes are called multimode fibers (core/cladding diameters of 50/125 μm and 62.5/125 μm) but the relative delay between the different modes introduce a huge restriction in long transmission links. For this reason, the fibers supporting a small number of optical modes have attracted a lot of interest and are now recognized as one of the most promising technologies to increase the transmission capacity.

In any MDM system, mode converters and mode (de)multiplexers are the key to combine/divide the different modulated signals. The behavior of weakly-coupled mode-selective fiber is based on coupled-mode theory [7], [8]. In fact, the coupling between the fundamental mode and the higher order modes are limited by the stability of the spatial-orientation [7], [8]. Recently, the use of a fiber based directional coupler for a MDM system at 1550 nm has been theoretically [7-9] and experimentally [10], [11] considered. However, the proposed system is based on the use of a specialty fiber with a two-mode behavior at 1550 nm.

The LP_{01} and LP_{11} modes propagate when standard single-mode fiber (SSMF), like SMF-28 with 8.2/125 μm core/cladding diameters, at 850 nm is employed, making a low cost solution without the need of any extra devices or design [12]. The optical modes have a high differential mode delay (DMD) value ensuring a negligible modal coupling along the SSMF link [13]. This band opens up the possibility of using low cost devices such as 10 Gb/s VCSEL [14].

Previously, the use of mode filters in a SSMF at 850 nm wavelength without taking advantage of the MDM benefits have been proposed [15], [16]. Besides these results, in order to increase the SSMF capacity using MDM at 850 nm band, a custom fiber coupler or mechanical mode converter has been theoretically [12] and experimentally [17] proposed and demonstrated. On one hand, the asymmetric fiber couplers permit to convert the LP_{01} mode into the LP_{11} mode with the added complexity of achieving the stringent fabrication tolerances required. On the other hand, a mechanical mode converter can be used to obtain a pure LP_{11} mode adding extra losses to the MDM link and requiring additional manual adjustment.

Additionally, a preliminary simulation and experimental demonstration of the correct demultiplexing of the 90:10 optical coupler has been reported [18]. The new study here presented is exhaustively performed taking into account the theory and experimental results in order to achieve the best performance.

In this letter, a comprehensive study of the LP_{01} and LP_{11} modes demultiplexing in commercially available standard single-mode couplers designed to operate at the 1550 nm band, and acting as mode multiplexer/demultiplexer at 850 nm, is presented.

Both the simulation analysis of the coupling efficiency in the 1550 nm and 850 nm bands and the experimental results of modal purity and insertion losses are considered.

2. Theoretical study

The basic concept of the MDM link is depicted in Fig. 1. It consists of two lasers emitting at 850 nm propagating the LP_{01} and LP_{11} modes in a standard single-mode fiber (SSMF). As the SSMF fiber behaves effectively as a two-mode fiber (TMF) at 850 nm, a bimodal optical link is obtained. Both modes will be coupled to the TMF using a commercial 2×1 optical coupler originally designed to operate at the 1550 nm wavelength. The behavior of the optical coupler at 850 nm operation will allow to multiplex the LP_{01} mode from the upper branch with the LP_{11} mode from the lower branch to the common output. The residual content of the LP_{11} mode at the upper branch and the LP_{01} mode at the lower branch will be eventually diverted to the other coupler output and discarded. At the receiver side, the same fiber coupler will act as a mode demultiplexer and each mode will be routed to the corresponding photodiode.

2.1 Coupling theory

According to two mode coupling theory, the optical fields along each optical fiber can be expressed as:

$$\vec{E}^A(x,y,z,t) = A(z)\vec{\varepsilon}^A_{mn}(x,y)e^{j(\beta^A_{mn}z-\omega t)}) \tag{1}$$

$$\vec{E}^B(x,y,z,t) = B(z)\vec{\varepsilon}^B_{pq}(x,y)e^{j(\beta^B_{pq}z-\omega t)}) \tag{2}$$

where $\vec{\varepsilon}^A_{mn}(x,y)$ and $\vec{\varepsilon}^B_{pq}(x,y)$ are the modal profiles in each optical fiber (mn in fiber A and pq in fiber B) while β^A_{mn} and β^B_{pq} are the propagation constants for both modes, respectively. Each individual mode is excited with their corresponding modal profile and propagation constant while the local modal profiles changes with the variation of the complex envelopes, *A(z)* and *B(z),* along the direction of propagation.

If we consider a simple case when power is launched only into *mode a* at *L*=0, the optical power in both outputs (direct (A) and coupled (B) paths) as a function of the input power $P_a(0)$ are [19]:

$$\frac{P_a(L)}{P_a(0)} = \left|\frac{A(L)}{A(0)}\right|^2 = \left(\frac{\kappa_{ab}\kappa_{ba}}{\beta_c^2}\right)\cos^2(\beta_c L) + \left(\frac{\delta}{\beta_c}\right)^2 \tag{3}$$

$$\frac{P_b(L)}{P_a(0)} = \left|\frac{B(L)}{A(0)}\right|^2 = \frac{|\kappa_{ba}|^2}{\beta_c^2}\sin^2(\beta_c L) \tag{4}$$

$$\delta = \frac{(\beta^B_{pq} + \kappa_{bb}) - (\beta^A_{mn} + \kappa_{aa})}{2} \tag{5}$$

$$\beta_c = \sqrt{\kappa_{ab}\kappa_{ba} + \delta^2} \tag{6}$$

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. Finally, the coupling efficiency for a length L is

$$\eta = \frac{P_b(L)}{P_a(0)} = \frac{|\kappa_{ba}|^2}{\beta_c^2}\sin^2(\beta_c L) \quad (7)$$

Thus, power is exchanged periodically between both modes with a coupling length

$$L_c = \frac{\pi}{2\beta_c} \quad (8)$$

where the maximum coupling is achieved when the phase mismatch is zero (δ=0). In this case, the propagation constants (and the refractive indexes) of both modes in the coupler will be the same.

2.2 Device structure

The optical coupler is employed as a mode multiplexer and mode demultiplexer of the LP_{01} and LP_{11} modes at 850 nm, as it is shown in Fig. 2. The structure is defined by the diameter of the fiber (D), the separation between cores (S) and the coupling length (L).

The fiber to be used for the optical coupler is the standard single-mode fiber; namely, SMF-28 from Corning Inc. (D=8.2 µm core diameter, Δ=0.36% refractive index difference and a SiO_2 cladding). At 850 nm, only two linear polarization (LP) modes are supported in SMF-28, behaving as a TMF. The refractive indexes are calculated employing the Sellmeier equation, obtaining a n_{core}=1.4577 and $n_{cladding}$=1.4525. Also, the eigenmodes' effective indices are calculated with the three-dimensional (3D) beam propagation method (3D-BPM), obtaining values of n_{LP01}=1.4564 and n_{LP11}=1.4545.

3. Simulation analysis

The optical coupler has been simulated at 850 nm for different gap, S (µm), and coupling length, L (mm) values. The maximum coupling efficiency is obtained when the Eq. (8) is fulfilled; therefore, for several gaps and lengths different coupling efficiencies will be achieved, as can be seen in Fig. 3 for the LP_{11} mode.

If the gap increases, the mutual coupling coefficients are reduced and, therefore, the optical coupler requires longer coupling lengths to achieve the maximum coupling efficiency.

When the optical coupler acts as a (de)multiplexer each mode is split to different outputs. The LP_{01} mode remains in the straight path whereas the LP_{11} mode is coupled to the cross path. Different coupler configurations (S, D, L) can be selected in order to achieve a perfect demultiplexing of the LP_{11} mode. It can be stated from Fig. 3 that the maximum separation between cores for a maximum coupling of the LP_{11} mode is around 9 µm (90 mm coupling length (yellow color band)). For wider separations, the mutual coupling coefficients are sufficiently separated and a very large length is needed to couple the LP_{11} mode. Thus, the commercial couplers designed to operate at 1550 nm will have a separation between cores shorter than 9 µm. Typically, commercial optical couplers present coupling lengths of few centimeters [20].

The simulation analysis was performed taking into account two different wavelengths, 1550 nm and 850 nm, in order to evaluate the behavior of the device in the design and operation wavelengths. To maximize the response of the optical coupler, the separation between cores is fixed at S=6 µm, with a coupling length up to L=20 mm.

Figure 4 shows the simulation results of the coupling efficiency when the optical coupler acts as demultiplexer. For the 1550 nm operation, only the LP_{01} mode is propagated, as it can be seen in Fig. 4(a). In this case, the maximum coupling efficiency from the straight path to the cross path takes place twice along the evaluated coupling length of L=20 mm. Thus, if we focus the attention in the highlighted region, a coupling ratio of 90:10 is obtained when the coupling length is L=17 mm. Figure 4(b) shows the coupling efficiency of the LP_{01} and LP_{11} modes operating at 850 nm. For the same highlighted region, L=17 mm, the LP_{01} mode obtained a coupling efficiency of 98% in the straight path and 1.76% in the cross path (that corresponds with an extinction ratio of 17.55 dB). However, the LP_{11} mode reaches a 100% in the cross path (for the same region) and 0% in the cross path. It can be stated that the commercial 90:10 optical coupler designed for 1550 nm can be used as multiplexer/demultiplexer of the LP_{01} and LP_{11} modes over SSMF fiber operating at 850 nm.

The simulation results are based on real fabrication parameters for a typical 90:10 optical coupler at 1550 nm, however, depending on the manufacturer and the fabrication method used, the coupler performance at 850 nm may differ.

4. Experimental validation

The schematic diagram of the experimental setup to obtain the near-field patterns of the LP_{01} and LP_{11} modes is shown in the Fig. 5. The vertical cavity surface emitting laser (VCSEL) transmitting at 850 nm and coupled to a SSMF pigtail propagates the LP_{01} and LP_{11} modes. When both modes enter the optical coupler they are demultiplexed in different output ports (LP_{01} in output A and LP_{11} in output B). The optical mode at each output will be visualized independently by manually selecting the corresponding output. For any single output, the mode is guided to the polarization controller (PC) to adjust the polarization. The collimator adjusts the size of the beam and the polarizer rotates from 0º to 360º the x-y polarization. Finally, a CCD camera (Thorlabs BC106-VIS) records the mode patterns.

The experiment is focused on demonstrating the demultiplexing of the LP_{01} and LP_{11} modes, more concretely the LP_{11} mode coupling. In order to check the coupling performance of the LP_{11} mode for both sine/cosine azimuthal variation (LP_{11a} and LP_{11b}) the PC and the polarizer will be jointly adjusted. By rotating 90 degrees the polarizer, it is possible to obtain both orthogonal polarization for any mode.

Different optical couplers with distinct coupling ratios have been measured in order to obtain a complete study of the different LP_{01} and LP_{11} modes. The insertion losses and the purity of the optical mode will be measured taking into account the received power and the modal profile of both LP_{01} and LP_{11} (LP_{11a}-LP_{11b}) modes at their respective coupler outputs.

Figure 6 shows the experimental near-field pattern of the LP_{01} and LP_{11} modes at the TMF output. First, when the polarizer is included in the beam path, the LP_{01} mode at the direct path output achieves a perfect near-field pattern for all optical couplers (99/1, 90/10, 80/20 and 60/40 coupling ratios at 1550 nm). At the cross path output, a perfect near-field LP_{11} mode profile can be achieved when the polarizer is set at orthogonal linear polarizations, marked as 0 and 90 degrees in Fig. 6 (corresponding in this case to the LP_{11a} and LP_{11b} orientation), for all couplers considered. However, if the polarizer is 45 degrees rotated, both polarizations are combined and a mixed LP_{11a}/LP_{11b} mode profile is obtained. At the direct path output, it was observed that a similar LP_{01} near-field pattern was obtained when changing the polarization. For simplicity, in Fig. 6 only one capture is represented for LP_{01}.

In terms of the insertion losses, the performance of the LP_{01} and LP_{11} modes at 850 nm differ from the specifications for the LP_{01} at 1550 nm. Table I summarizes the results. The insertion losses have increased in both branches; being 7.4 dB, 4.9 dB, 6.7 dB and 6.9 dB at the direct path and, 26.2 dB, 12.9 dB, 21.9 dB and 23.8 dB at the cross path, respectively, when the total optical power at the coupler's input is taken as a reference. Thus, the only optical coupler that achieved a similar behavior at 850 nm than the specifications at 1550 nm was the 90:10 coupler.

From the LP_{11a} and LP_{11b} near-field pattern shown in Fig. 6, the corresponding modal profiles along the major axis are shown in Fig. 7. The results of the four optical couplers (99:1, 90:10, 80:20 and 60:40) are compared. Both LP_{11} orientations show an excellent purity after the demultiplexing process. In some cases, there is a minor interference of the LP_{01} (shown as a non-zero intensity at the center of the fiber, position=0 µm) due to the use of optical couplers which are designed to operate at 1550 nm and not optimized for 850 nm operation. However, if the optical coupler would be specifically designed for 850 nm operation, the (de)multiplexing of both modes would be perfect [12]. In the LP_{11a} case, the couplers with a coupling ratio of 99:1 and 90:10 showed in the Fig. 7(a) obtained the best purity with a 97%. The rest of the couplers achieved a 90%. A similar performance is obtained with the LP_{11b} orientation, but now only the coupler 99:1 (Fig. 7(b)) reached the best purity (97%). A purity better than 90% is obtained for the other three couplers.

5. Conclusion

This paper proposes and demonstrates the simulation and experimental analysis of the LP_{01} and LP_{11} modes at 850 nm when the optical coupler acts as demultiplexer.

The simulation results presents that the 90:10 optical coupler can multiplex/demultiplex the LP_{01} and LP_{11} modes at 850 nm (for a S=6 µm and L=17 mm), obtaining a coupling efficiency of 98% and 100%, respectively. Moreover, the experimental results point out the good performance of the different optical couplers at 850 nm. In terms of the insertion losses, the 90:10 optical coupler achieved the best performance with insertion losses of 4.9 dB and 12.9 dB, respectively. The purity of the demultiplexed optical modes was 98.4% for the LP_{01} mode and higher than 90% for both LP_{11a} and LP_{11b} modes.

In conclusion, this results open up the possibility to simplify the MDM system using SSMF at 850 nm without the need of mode converters, mode rotators or mode strippers for mode multiplexing and demultiplexing.

6. Acknowledgement

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Captions

Fig. 1. MDM transmission using standard single-mode couplers as multiplexer/demultiplexer at 850 nm.

Fig. 2. 3D sketch of the structure of the fiber coupler mode (de)multiplexer.

Fig. 3. LP_{11} coupling efficiency in a SMF-28 fiber coupler as a function of the coupler gap and length.

Fig. 4. Different coupling efficiencies when both LP_{01} and LP_{11} modes are excited and the LP_{11} mode is demultiplexed at the cross path.

Fig. 5. Experimental setup for the measurement of the near-field patterns for the LP_{01} and LP_{11} modes at the direct and cross paths of the fiber coupler.

Fig. 6. Experimental near-field pattern at both coupler outputs (A: direct path, B: cross path) for different optical couplers and pattern rotation (cross-path: 0, 45 and 90 degrees) with/without polarizer in beam path for the LP_{01} mode and LP_{11a} and LP_{11b} modes.

Fig. 7. Experimental modal profiles at the TMF output at 850 nm for the four optical couplers in the case of the LP_{11} with their two orthogonal polarizations: (a) LP_{11a} and (b) LP_{11b}

Figures

Fig. 1

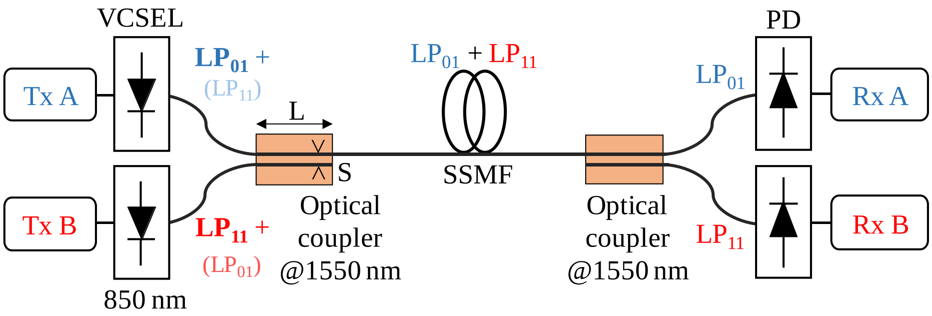


Fig. 2

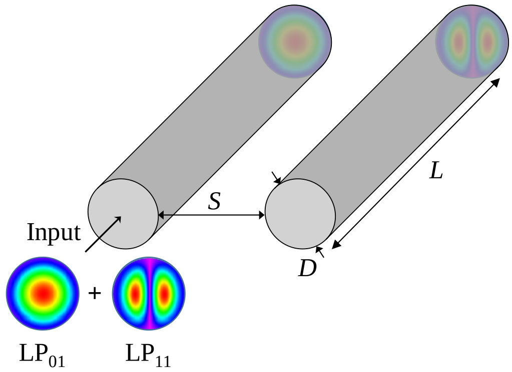


Fig. 3

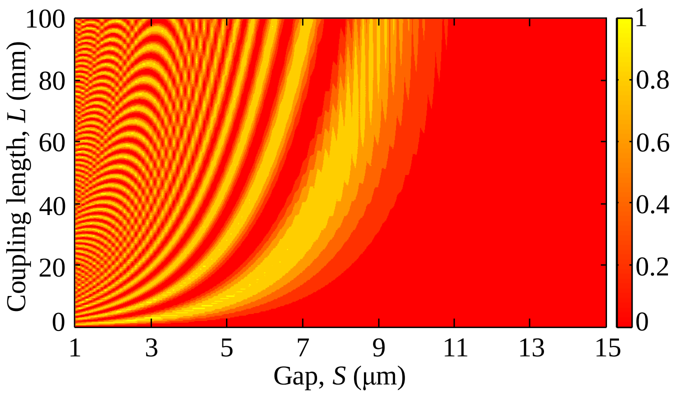
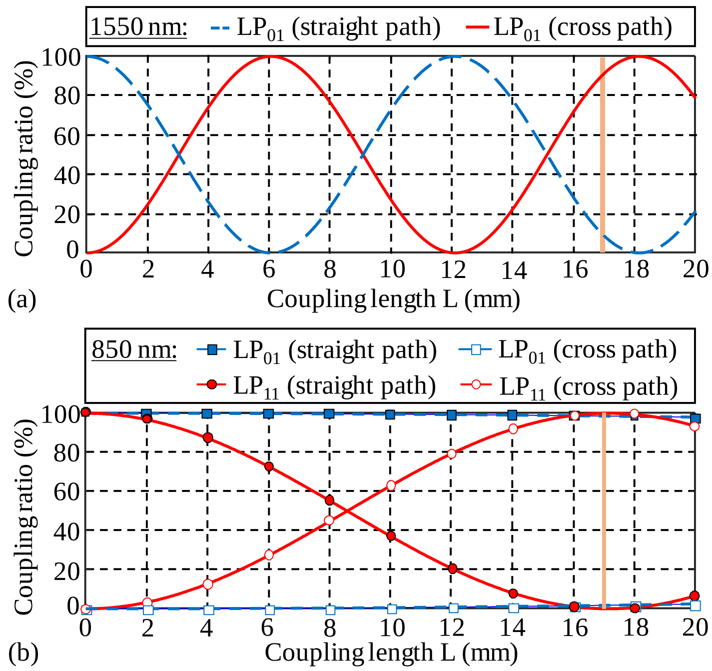
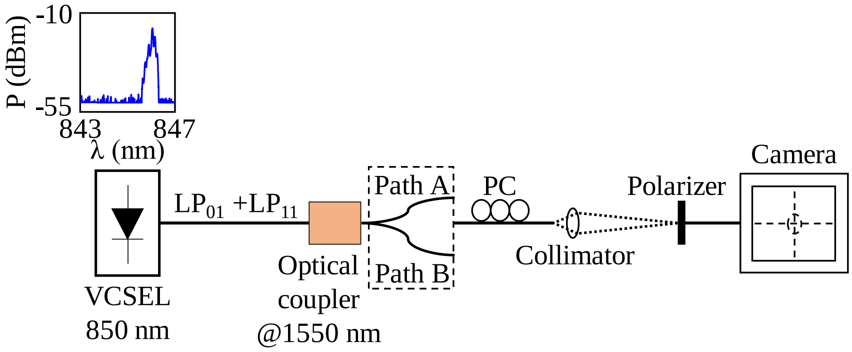


Fig. 4



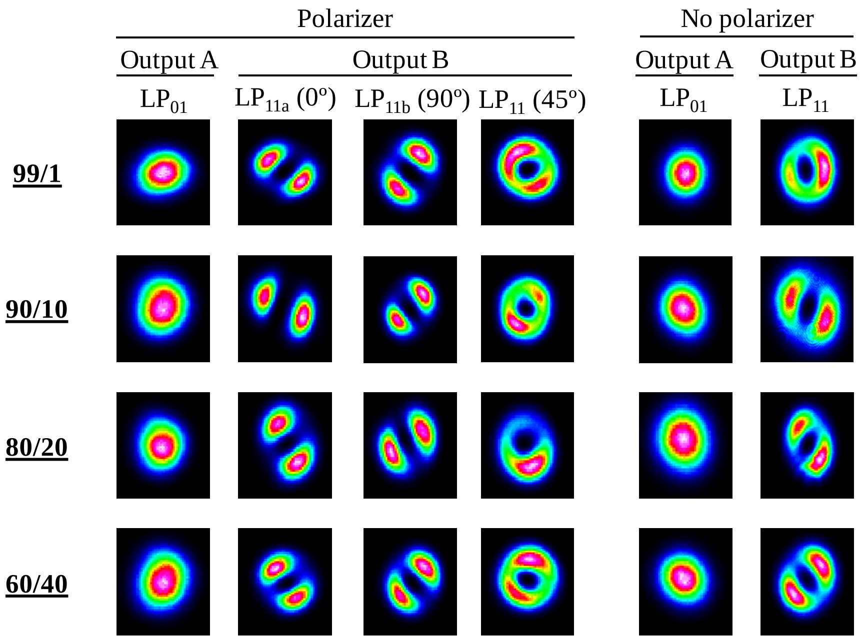
1550 nm: LP01 (straight path) LP01 (cross path)
Coupling ratio (%)
Coupling length L (mm)
(a)
850 nm: LP01 (straight path) LP01 (cross path)
LP11 (straight path) LP11 (cross path)
Coupling ratio (%)
Coupling length L (mm)
(b)

Fig. 5



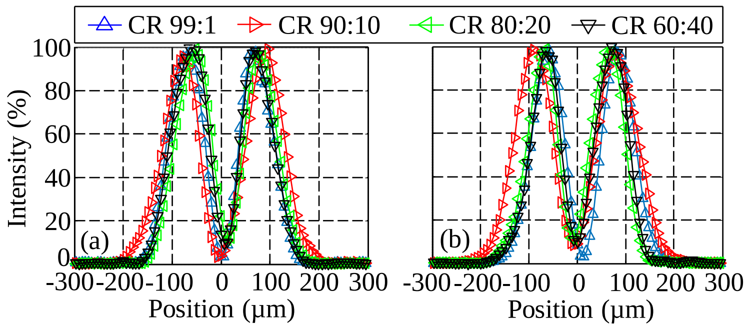
P (dBm)
-10
-55
843
847
λ (nm)
LP01 +LP11
VCSEL
850 nm
Optical
coupler
@1550 nm
Path A
Path B
PC
Collimator
Polarizer
Camera

Fig. 6



Polarizer
No polarizer
Output A
Output B
Output A
Output B
LP01
LP11a (0°)
LP11b (90°)
LP11 (45°)
LP01
LP11
99/1
90/10
80/20
60/40

Fig. 7



CR 99:1
CR 90:10
CR 80:20
CR 60:40
Intensity (%)
100
80
60
40
20
0
(a)
(b)
-300 -200 -100 0 100 200 300
Position (µm)
-300 -200 -100 0 100 200 300
Position (µm)

Tables

Table 1. Commercial optical couplers at 1550 nm and 850 nm

Optical couplers (@1550 nm)		Optical couplers (@850 nm)
CR (%)	IL (dB)	IL (dB)
99/1	0.2/20.8	7.4/26.2
90/10	0.7/9.2	4.9/12.9
80/20	1.1/7.2	6.7/21.9
60/40	2.4/4.1	6.9/23.8