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Mode Conversion for Mode Division Multiplexing at 850 nm in Standard SMF

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

Abstract— **A mechanical mode converter for Mode Division multiplexed (MDM) systems over SSMF at 850 nm is proposed and evaluated experimentally by the transmission of OOK modulated optical signals. The proposed mode converter is based on a periodic structure defined by the grating period (Λ) parameter and the number of mode coupling points, N. A mechanical grating with $N=50$ points and a tunable grating period (Λ form 440 μm to 456 μm) has been designed offering a 124 nm tuning bandwidth. The LP_{01} mode to LP_{11} mode conversion has been experimentally assessed and a conversion efficiency of 89 % has been achieved in the designed device. Optical transmission of OOK modulated signals with 1.25 Gb/s and 2.5 Gb/s bitrates on LP_{01} mode or a converted LP_{11} mode is demonstrated achieving BER < 10^{-9} after 1 km optical transmission over SSMF at 850 nm.**

Index Terms— **Mechanical mode converter, mode stripper, mode conversion, mode division multiplexing.**

I. INTRODUCTION

T HE availability of cost effective vertical cavity surface emitting lasers (VCSEL's) at 850 nm combined with optimized designs of multimode fiber (MMF) have been stablished as a low cost solution for short range high speed optical data links [1], [2]. The use of 850 nm VCSEL's for transmission over SSMF constitutes a promising low cost solution to improve the capacity and the link reach provided by MMF [3]. Using the 850 nm wavelength opens up the possibility to multiplex two linear polarization (LP) modes when standard single mode fiber (SSMF) is chosen as the transmission media, compared with more than 100 modes if multimode fiber (MMF) were employed. Fibers that propagates several modes are called "Few Mode Fibers" (FMF) or even "Two Mode Fibers" (TMF) to distinguish them from MMF, and can be designed to operate at short wavelengths [4].

Spatial-Division Multiplexing (SDM) or Mode-Division Multiplexing (MDM) are promising techniques to increase the capacity of fiber optic communication networks [5], [6]. MDM increases the fiber capacity by means of the parallel transmission of different information through the available spatial modes at a specific wavelength. Specialty fibers or free-space transmission are usually considered on the MDM experiments instead of the ubiquitous SSMF [4], [7].

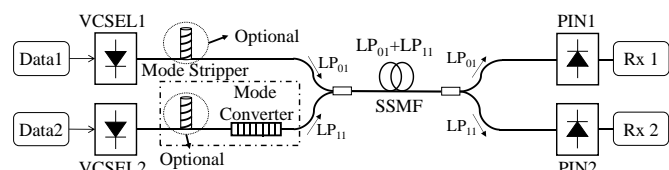In any MDM system, mode converters and mode

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

(de)multiplexers are required to combine and split the modes. Mode converters and multiplexers based on spatial light modulators or q-plates have been successfully used in MDM experiments [4], [7] but the devices based on fused fiber couplers offer a compact solution, with less losses and with direct integration with optical fiber. Both, symmetric (same fiber type) and asymmetric (different fiber type) fused fiber couplers have been proposed as mode converters and mode (de)multiplexers [8], [9]. Asymmetric couplers are required in order to achieve mode conversion, whereas both asymmetric and symmetric couplers can be advantageously used as (de)multiplexer. Unfortunately, the fabrication tolerances required by the asymmetric couplers are more difficult to fulfill than the equivalent tolerances for the symmetric device. However, the use of symmetric couplers as (de)multiplexer requires an additional device to accomplish the mode conversion (LP_{01} to LP_{11}) in the transmitter as shown in Fig. 1 [8].

Mode conversion based on a mechanical grating for a MDM system operating at 1550 nm has been theoretically and experimentally proposed [10], [11]. The mechanical mode converter transforms the LP_{01} to LP_{11} by applying pressure into the fiber [11]. This mechanical grating was designed to work at 1550 nm by selecting the appropriate grating period. However, the proposed system requires the use of a specialty fiber with a two mode behavior at 1550 nm. Instead, the use of SSMF as the optical media at the 850 nm band would benefit from the broad availability of SSMF-based infrastructure in current networks.

In this letter, the use of a mechanical converter for MDM in SSMF at 850 nm is first analyzed. Following the analysis, a mode converter for operation at 850 nm in SSMF is designed and fabricated. Finally, the transmission performance employing OOK modulation is experimentally evaluated.
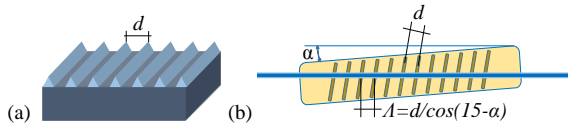
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Fig. 2. Mechanical Mode Converter: a) Structure, b) Design parameters.

Fig. 3. Setup for the conversion from LP_{01} to LP_{11}.

Fig. 4. Grating period (Λ) as a function of the wavelength.

II. MODEL

A. System

The MDM system including the mechanical mode converter is depicted in Fig. 1. At the transmitter, two VCSEL sources are modulated by different data sources. The VCSEL's are coupled to SSMF patchcords. In general terms, both LP_{01} and LP_{11} could be excited in the fiber depending on the misalignment (lateral displacement or angle of incidence) of the laser light from the VCSEL to the core of the fiber. A mode stripper is placed after each VCSEL in order to eliminate any residual LP_{11} content without reducing the LP_{01} power. The LP_{01} mode from the upper branch is directly sent to the fiber coupler acting as mode multiplexer. In the lower branch the LP_{01} is converted to LP_{11} by using the mechanical mode converter and then sent to the fiber coupler when it is multiplexed with the optical signal coming from the upper branch. The multiplexed signals travel over the SSMF acting as a two-mode fiber at the 850 nm band. At the receiver, the LP_{01} and LP_{11} are demultiplexed by using the same device used as multiplexer in the transmitter.

B. Mechanical Mode Converter

A mechanical mode converter is a periodic structure defined by a grating period (Λ) with N coupling points that create a periodic perturbation on the optical fiber, as depicted in Fig. 2. The grating period defines the wavelength where the efficiency to convert the LP_{01} to LP_{11} is maximum. The conversion efficiency can be expressed as [12]:

$$\frac{P_{11}}{P_{01}} = \frac{\sin^2\left(\kappa \cdot L \sqrt{1 + \left(\frac{\delta}{\kappa}\right)^2}\right)}{1 + \left(\frac{\delta}{\kappa}\right)^2} \quad (1)$$

$$\delta = \frac{1}{2}\left\{\frac{2\pi}{\lambda}\left(n_{LP01} - n_{LP11}\right) - \frac{2\pi}{\Lambda}\right\} \quad (2)$$

where P_{01} is the power of the LP_{01} mode, P_{11} is the power of the LP_{11} mode, κ is the coupling coefficient, L is the grating length, δ is the detuning parameter, λ is the wavelength, n_{LP01} and n_{LP11} are the effective refractive indexes of the LP_{01} and LP_{11} modes and Λ is the grating period. Equation (1) shows that the maximum coupling will take place when $\delta = 0$. Therefore, from (2) it is possible to define the grating period as:

$$\Lambda = \frac{\lambda}{n_{LP01} - n_{LP11}} \quad (3)$$

In our case, the relative inclination of the grating axis with respect to the fiber (α in Fig. 2) can be adjusted by 15 degrees. Thus, the effective grating period, Λ, can be tuned between d and $d/cos(15)$ when the separation of the grating grooves is d. This variation in the effective grating period adds flexibility to adjust the modal converter to the fiber specific characteristics and the wavelength emitted by the laser.
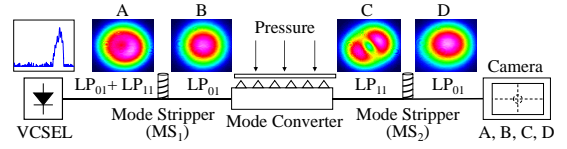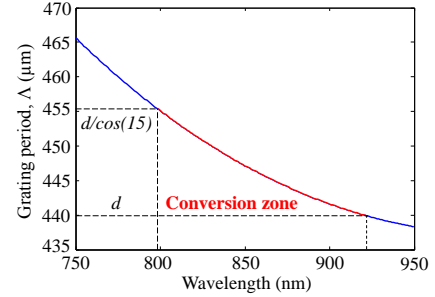
Finally, for a periodic structure with equal pressure in each coupling point, the conversion efficiency would be [10]:

$$\frac{P_{11}}{P_{01}} = \sin^2\left(N \cdot \sin^{-1}(\kappa)\right) \quad (4)$$

C. Grating

The mechanical mode converter will be used with SMF-28 fiber from Corning Inc. (8.2 µm core diameter, $\Delta = 0.36\%$ refractive index difference and SiO_2 cladding). Sellmeier equation has been used to calculate the refractive and the modal effective indexes at 850 nm. These are $n_{core} = 1.4577$, $n_{cladding} = 1.4525$, $n_{LP01} = 1.4564$ and $n_{LP11} = 1.4545$. Finally, the optimum grating period to transform the LP_{01} to the LP_{11} at 850 nm is $\Lambda = 447.36$ µm.

According to (3) the grating period depends on the wavelength, both directly and indirectly through the wavelength dependence of the modal effective indexes. This dependence is shown in Fig. 4.

A mechanical mode converter has been fabricated with $N = 50$, $d = 440$ µm and $L = 2.2$ cm in order to maximize the number of periods in the grating and to center the wavelength range of the device at 850 nm. An effective grating period, Λ, between 440 µm and 456 µm can be obtained when $d = 440$ µm. Thus, this mode converter can transform LP_{01} to LP_{11} in a 124 nm bandwidth around 850 nm (from 798 nm to 922 nm, marked as conversion zone in Fig. 4) if SMF-28 fiber is used.

III. MODE CONVERSION EFFICIENCY

The mechanical mode converter transforms a particular mode to the next higher order mode through the grating period. The setup depicted in Fig. 3 has been used to experimentally demonstrate the conversion efficiency of the mechanical mode converter previously designed. The optical signal generated in an 850 nm VCSEL is coupled to a patchcord of bare SMF-28 fiber. The output of the VCSEL will be a combination of both LP_{01} and LP_{11} modes. The two linear polarization (LP) modes coming from the VCSEL are guided to the first mode stripper (MS_1) to erase the LP_{11} content and obtain a pure LP_{01} mode. The mechanical mode converter transforms the LP_{01} to the LP_{11}
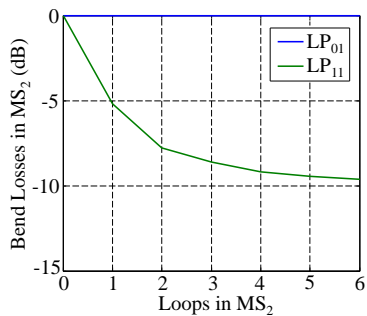
Fig. 5. Bend losses in the MS_2 as a function of the loop number.

Fig. 6. Modal profiles in SSMF: a) LP_{01} mode in B2B transmission, b) LP_{11} mode B2B transmission, c) LP_{01} mode after 1 km, d) LP_{11} mode after 1 km.

mode. A CCD camera Beam Profiler will be placed in the positions A, B, C or D in order to visualize the modal profile. The camera in the C position permits to properly adjust the pressure at the mechanical mode converter measuring the power obtained and visualizing the modal profile.

Once the LP_{11} is obtained, a second mode stripper (MS_2) is used to erase the converted LP_{11}. The LP_{11} power content is determined as the power difference between points B-D, as the MS_2 will only remove the LP_{11} mode. Finally, the conversion efficiency will be obtained as the ratio between this result and the total optical power after mode conversion (point C).

The designed mechanical grating will be placed on a stand as described in [10] in order to manually adjust the pressure level applied on the fiber and the relative angle between the grating and the fiber. The periodic perturbation produced by the grating will transform the LP_{01} mode to the LP_{11} mode. A low level pressure is required in the mechanical mode converter to achieve the mode transformation. If the pressure is too high, the LP_{01} power will be attenuated and the conversion efficiency will be reduced. It is important to point out that the fiber used in the setup is SMF-28 fiber with a 250 μm cladding and no additional coating. The thin cladding makes it easier to apply the pressure produced by the mechanical mode converter to the fiber core without breaking the fiber.

The mode strippers used in the setup are made by coiling the SSMF fiber around a cylinder of a certain diameter in order to erase the LP_{11} mode without losing the power content of the LP_{01} mode. Different diameters (from 0.6 cm to 1.2 cm) have been studied, obtaining an optimum size of 1.0 cm, which eliminates completely the LP_{11} mode after a few loops without damaging the LP_{01} mode (losses < 0.01 dB). The mechanical mode converter configuration (pressure level, and relative angle between fiber and grating) were selected by using the CCD camera at the output of the mode converter and choosing the purest LP_{11} mode profile as shown in Fig. 6b.

It has to be taken into account that the mode converter induces insertion losses around 0.2-0.5 dB depending on the pressure level applied on the fiber core. For the optimum mode converter configuration these losses are equal to 0.5 dB.

In order to measure the conversion efficiency, the difference in optical power between the points B-D in Fig. 3 must be measured when the MS_2 mode stripper removes all the LP_{11} mode content. The number of loops applied to the fiber in this mode stripper will define the attenuation level suffered by the LP_{11} mode. As the number of loops increases, the power level in point D is reduced until the LP_{11} is fully removed and the residual LP_{01} mode content will be the only term to be
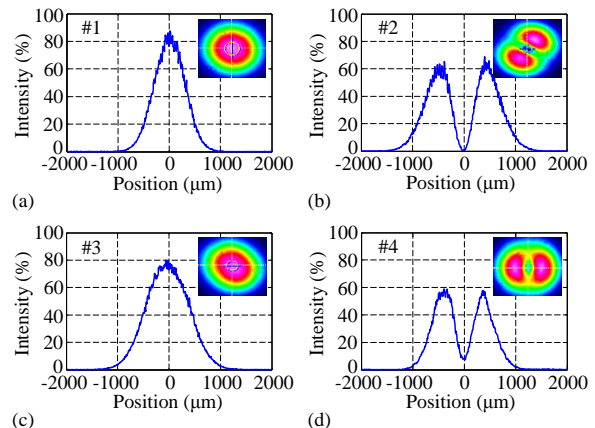
measured. In Fig. 5 the optical attenuation between points B-D is shown for 0 to 6 loops in the MS_2 mode stripper (1.0 cm diameter). From these results, it is clear that after 6 loops the LP_{11} content is fully removed. The residual LP_{01} content is shown to be 9.5 dB below the LP_{11} mode content, which corresponds to a LP_{01} to LP_{11} mode conversion efficiency of 89 % and a coupling coefficient of κ=0.025.

IV. MODE TRANSMISSION EXPERIMENT

The MAX3996 evaluation board from Maxim Integrated will be used to assess the data transmission performance of the LP_{01} and LP_{11} modes over SSMF fiber at 850 nm. This board is equipped with the MAX3996 VCSEL laser driver and a maximum data rate of 2.5 Gb/s can be selected. An 850 nm VCSEL with an electrical bandwidth greater than 1 GHz has been added to the evaluation board. This VCSEL is coupled to a SSMF pigtail with an optical output power of -13 dBm.

The use of the 850 nm band in SSMF is aimed at short reach links due to the high losses (~2 dB/km) of the fiber at this wavelength. Due to an additional limitation on the output power coupled to the SMF-28 from the available 850 nm VCSEL, data transmission measurements were limited to 1 km reach.

In the first experiment, the evolution of the LP_{01} and LP_{11} modes through the 1 km link has been assessed by transmitting the unmodulated optical signal alternatively with and without pressure applied to the mode converter. The corresponding mode profiles for LP_{01} and LP_{11} are depicted in Fig. 6, where the results for back-to-back transmission (pictures #1 and #2) and along 1 km of fiber (pictures #3 and #4) are compared. The mode profiles are maintained at the output of the link and the viability of the MDM system at 850 nm over SSMF would be ensured if both modes were transmitted simultaneously and the proper mode (de)multiplexers were available. Both modes show an excellent stability after 1 km long transmission. In both cases, there is a minor interference of the alternate mode when the mode profile is taken after 1 km of fiber. The LP_{01} mode profile after 1 km is slightly broadened if compared to the B2B case due to a minimal LP_{11} power level. In the LP_{11} case, the intensity level just in the center of the fiber is not exactly zero after 1 km of fiber what corresponds to the presence of a reduced level of the LP_{01} mode. If we compare the modal profiles in Fig. 6b and Fig. 6d, the interference of the LP_{01} mode
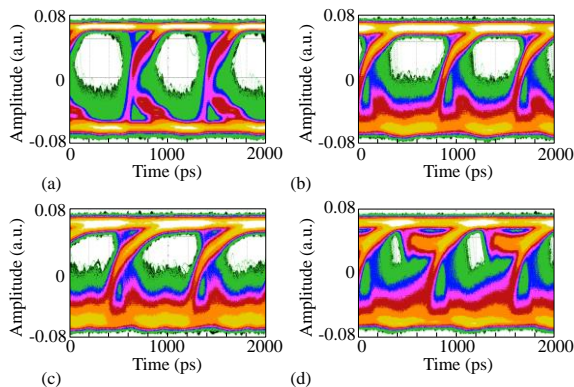
Fig. 7. Eye diagram for the LP_{01} and LP_{11} modes at 1.25 Gb/s: a) B2B LP_{01}, b) B2B LP_{11}, c) 1 km LP_{01} and d) 1 km LP_{11}.
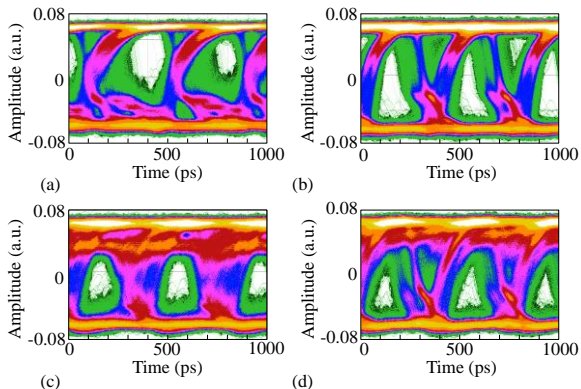
Fig. 8. Eye diagram for the LP_{01} and LP_{11} modes at 2.5 Gb/s: a) B2B LP_{01}, b) B2B LP_{11}, c) 1 km LP_{01} and d) 1 km LP_{11}.

in Fig. 6d corresponds to a relative intensity of the LP_{01} mode 10 dB below the intensity of the LP_{11} due to the modal coupling in the optical connector. This behavior is due to the mode coupling (LP_{01} to LP_{11} and LP_{11} to LP_{01}) induced by the connector between the bare fiber at the mode converter and the fiber span as it would happen with any connector in any TMF/FMF link. The elimination of this connector by using the same fiber in the converter and in the fiber span would avoid any potential mode crosstalk. No mode crosstalk is expected to be due to the mode coupling along the fiber as the difference between the effective indexes of both modes is $1.3 \cdot 10^{-3}$ [13].

In order to test the link capability along 1 km we will transmit the individual modes modulated by an OOK signal with a $2^{31}-1$ pseudo random bit sequence (PRBS) at 1.25 Gb/s and 2.5 Gb/s. The evaluation can be done through the measurement of the quality factor (Q), which determines the quality of the eye diagram and it is directly related to the Bit Error Rate (BER).

Fig. 7 shows the eye diagrams for the LP_{01} and LP_{11} modes at a bit rate of 1.25 Gb/s. For the B2B case, both modes have an open eye diagram with quality factors around Q≈19 and Q≈8, respectively. This difference between quality factors is due to the conversion losses from LP_{01} to LP_{11}; however, it is important to mention that both signals have a quality factor higher than Q=6, corresponding to a BER=10^{-9}. After the 1 km transmission, the quality of the eye diagrams have been slightly reduced due to the attenuation of the fiber and the influence of the fiber connectors. Anyway, the final Q value for the LP_{01} and LP_{11} is approximately Q≈6.8. In this case, both modes can be transmitted and received correctly at 1.25 Gb/s along 1 km.

Fig. 8 shows the same transmission as the Fig. 7 but changing the bit rate to 2.5 Gb/s. It is important to point out that the bandwidth limitation of the VCSEL used for the experiments is affecting the transmission even for the B2B case as shown in Fig. 8 a) and b), with a quality factors around Q≈9 and Q≈8, respectively. After 1 km transmission, the LP_{01} and LP_{11} suffer almost the same distortion at 2.5 Gb/s that at 1.25 Gb/s. The resulting quality factors for the LP_{01} and LP_{11} after 1 km are both around Q≈6.2, again higher than Q=6.

V. CONCLUSION

In this letter, we have proposed and evaluated experimentally the use of a mechanical mode converter at 850 nm to achieve mode transformation from LP_{01} to LP_{11} in SSMF.

The design of the mechanical grating is centered at 850 nm but it can be tuned in a 124 nm bandwidth. The tunability can be advantageously used to adapt the mode converter to tolerances in fiber specifications or laser performance. The mechanical mode converter has been shown to offer 89 % LP_{01} to LP_{11} conversion efficiency. The stability of both modes (LP_{01} and converted LP_{11}) has been proved in a 1 km SSMF link.

Finally, data transmission over 1 km at 1.25 Gb/s and 2.5 Gb/s OOK signal was achieved obtaining a quality factor higher than Q=6 (BER=10^{-9}) for both modes. The link distance and achieved bitrate were limited by the reduced output power and modulation bandwidth of the VCSEL source.

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