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A Converter for Transmission with Singlemode Performance on OM2/3/4/5 Multimode Fibers

Lars Grüner-Nielsen, *Member, IEEE,* Michael Stübert Berger *Member, IEEE,* Mads Nielsen, Neethu Mariam Mathew, and Karsten Rottwitt *Member, IEEE*

***Abstract*—A converter from a singlemode fiber to the fundamental mode of an OM2, OM3, OM4, or OM5 type multimode fiber is presented and is used to transmit 100 GbE with no detected errors over 1600 m multimode fiber using commercial transceivers. The converter is based on splicing a short length of few-mode fiber between the singlemode fiber and the multimode fiber. The few-mode fiber is designed so that the fundamental mode of the few-mode fiber has a good mode overlap with the fundamental mode of the multimode fiber. To suppress any higher order modes in the few-mode fiber, an optimized bend based mode stripper is used. The converter has a low loss of 0.35 dB, lower than previous reported solution. The converter do, opposite to previous suggested solutions, not include any free space part or mechanical connections, which assures low loss and cross talk as well as good long term stability.**

***Index Terms*—Space division multiplexing, crosstalk, multimode fiber**

I. Introduction

TODAY there is a large base of installed multimode fibers (MMF) in data centers and office interconnects. Methods to upgrade the capacity and reach of these fibers are therefore of interest. Lately, there has been successful demonstrations of use of standard multimode fibers for mode division multiplexed transmission [1], [2]. However, there is still quite some work needed before these solutions can be used together with standard commercial transceivers. For example, the solution of [1] requires use of multimode photo detectors while the solution of [2] requires use of two photo detectors for the degenerate modes. A much more straight forward upgrade path is to use only the fundamental LP_{01} mode [3]–[5]. The multimode fiber can then get the same performance as a standard singlemode fiber (SSMF) and standard singlemode transceivers can be used for transmission.

To obtain singlemode performance on a MMF, three conditions must be met: 1. The singlemode input and output ports of the transceiver should be connected to the LP_{01} mode of the MMF with low loss and low coupling to other modes. 2. There should be a low coupling from the fundamental mode to higher order modes during propagation in the MMF. 3. Any splices or connectors, a long the fiber, should have low coupling from the fundamental mode to higher order modes.

The critical component is the converter from the singlemode input and output of the transceiver to the multimode fiber. In [3], a converter based on multi plane light conversion is used. In [4], a fiber adapter with a short piece (16 mm) of singlemode fiber, which has a mode field diameter matching the multimode fiber is used. Finally [5] use a laser written photonic integrated circuit to couple from the SSMF to the MMF.

In this work, a singlemode fiber to multimode fiber converter based on a short length (0.5-1 meter) of few-mode fiber with a mode stripper spliced between the singlemode fiber and the multimode fiber is proposed. The converter is designed for use with standard 50/125 µm multimode fibers (OM2/3/4 or 5), which represents the major part of installed multimode fibers.

II. Fundamental mode launch

The basic idea of this work is to use a short length of intermediate fiber (IMF) between the SSMF and the MMF. The IMF is designed to have a fundamental mode with good overlap with the fundamental mode of the MMF. In this work, we use a four mode IMF, which is much more robust to bends than a singlemode IMF as for example used in [4]. Contrary to the work of [4], where connector interfaces are used, we splice the IMF to the SSMF and the MMF, which makes it possible to get lower insertion loss, better long term stability and minimize extra cross talk and loss due to offset in the coupling between the fibers.

As the IMF, an OFS two mode step index fiber (TMSIF) (supporting two LP mode at 1550 nm) [6], which at 1300 nm guides 4 LP modes (LP_{01}, LP_{11}, LP_{21}, and LP_{02}), is used. At 1300 nm, it has a mode field diameter for LP_{01} of 14.4 µm , which is close to the LP_{01} mode field diameter of 14.0 µm for the 50/125 µm MMF. For comparison the mode field diameter of a standard singlemode fiber is 9.2 µm at 1300 nm.

In table I modeled cross talk (XT) for splicing of a SSMF to a 50/125 µm MMF and in table II modeled XT for a TMSIF spliced to a 50/125 µm MMF are shown. The XT from the LP_{01} mode of the SSMF/TMSIF to the first 6 mode groups of the MMF are shown. The XT is found by first calculating the optical mode distributions $E(\phi, r)$ using a mode solver on the refractive index profile of the fibers. The mode solver, solve the scalar wave equations, using the finite difference method and is programmed in Python by the authors. Then, the XT is found from the overlap integrals between the modes Eq. 1.

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TABLE I: Modeled cross talk in dB for splice between SSMF and MM 50/125 fiber @1300 nm.

Mode group	LP mode no	XT offset 0	XT offset 0.1 µm	XT offset 1 µm
MG2	11	-54	-33	-14
MG3	02 21	-7.9	-7.9	-8.3
MG4	12 31	-56	-37	-19
MG5	03 22 41	-14	-14	-14
MG6	13 32 51	-57	-41	-23

TABLE II: Modeled splice cross talk in dB between LP_{01} of TMSIF and MM 50/125 fiber @1300 nm.

Mode group	LP mode no	XT offset 0	XT offset 0.1 µm	XT offset 1 µm
MG2	11	-52	-37	-18
MG3	02 21	-34.9	-34.8	-31.6
MG4	12 31	-55	-45	-32
MG5	03 22 41	-22	-22	-22
MG6	13 32 51	-56	-45	-30

$$XT = \frac{\sum_i \int_0^\infty \int_0^{2\pi} E_{01a}(\phi-\phi_0, r-r_0) E^*_{ib}(\phi, r) d\phi r dr}{\int_0^\infty \int_0^{2\pi} E_{01a}(\phi-\phi_0, r-r_0) E^*_{01b}(\phi, r) d\phi r dr}, \quad (1)$$

where $E_{01a}(\phi, r)$ is the mode distribution for LP_{01} of either the SSMF or the TMSIF. $E_{ib}(\phi, r)$ is the mode distributions for the MM 50/125 fiber and i is summed over all the spatial modes of the mode group for which the XT is calculated (e.g. for MG3: LP_{02}, LP_{21a}, and LP_{21b}). r_0 is the radial offset and ϕ_0 is the angle along which the offset is made. In our calculations we use $\phi_0 = 45°$. The XT are calculated for both an ideal splice without any offset, for a typical offsets of 0.1 µm, and finally for a very large offset of 1 µm in the splice. Even without any offset, a considerable cross talk is observed for the SSMF-MMF splice for mode group 3 and 5, while a much lower cross talk is observed for the TMSIF-MMF splice even for an offset as high as 1 µm.

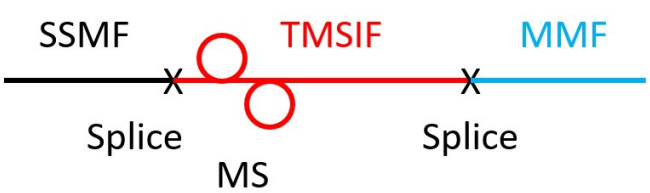


Fig. 1: Fundamental mode launch. SSMF: Standard single-mode fiber, TMSIF: Two mode step index fiber, MMF: Multimode fiber, MS: Mode stripper (two perpendicular bends).

The proposed configuration of our fundamental mode launch is shown in figure 1. To suppress any higher order modes generated in the SSMF-TMSIF splice, a mode stripper made of two perpendicular bends consisting each of two turns around a 12.5 mm mandrel is used.

To evaluate the mode launch, the setup of figure 2 is used (section 4. of [7]). The BBS is a superluminescent diode from Exalos type EXS210057-02. The loss (relative to a direct SSMF pigtail connection between the PC output and the OSA) is measured for 10 randomly chosen positions of the polarization controller. The loss is measured for several polarizations because the mode cross talk is known in some cases to be polarization dependent [7]. The loss is evaluated around 1300 nm as this is the preferred wavelength for short reach transceivers due to the low chromatic dispersion of SSMF around this wavelength. Also 50/125 µm MMF have low dispersion here. The typical zero dispersion wavelength is 1310 nm for SSMF and 1330 nm for 50/125 µm MMF.

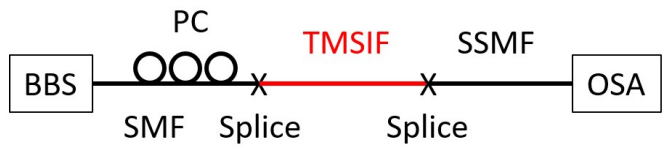
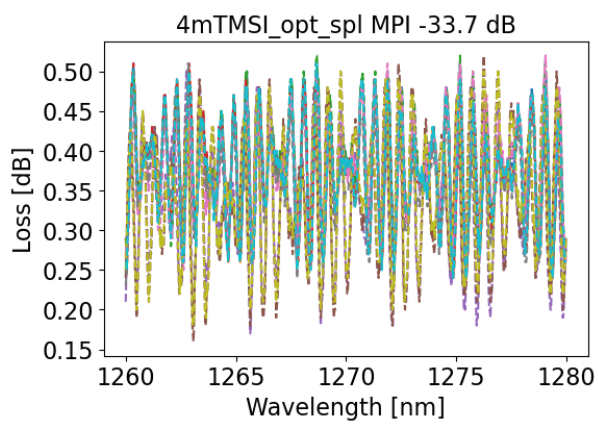
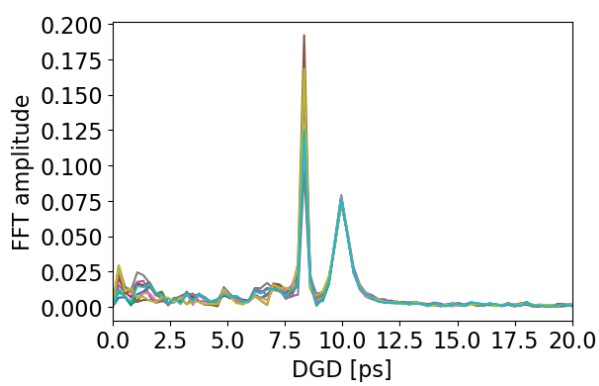


Fig. 2: Measurement setup. BBS: Broadband light source, PC: Polarization controller, OSA: Optical spectrum analyzer



(a)



(b)

Fig. 3: (a) Measured loss spectra for 4 m TMSIF spliced to SSMF with optimal splices for 10 different input polarizations. (b) Fourier transform of spectra of figure 3a.

Measured loss is shown in figure 3a. An average loss of 0.36 dB is observed for the two TMSIF-SSMF splices. This low loss is obtained despite the large difference in mode field diameter by use of a very long splice time of 80 seconds on a Vytran filament splicer. The multi path interference (MPI), defined as the ratio between the power in the parasite modes

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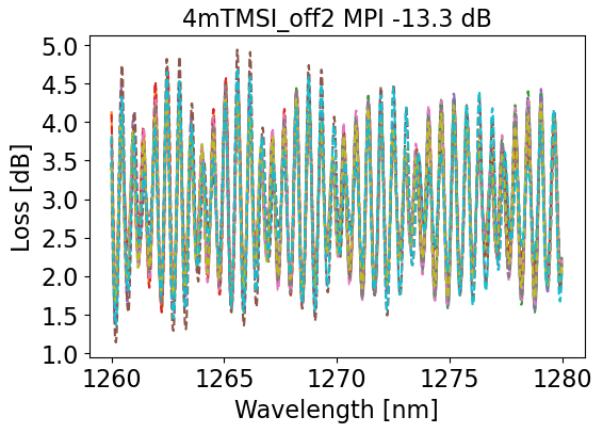
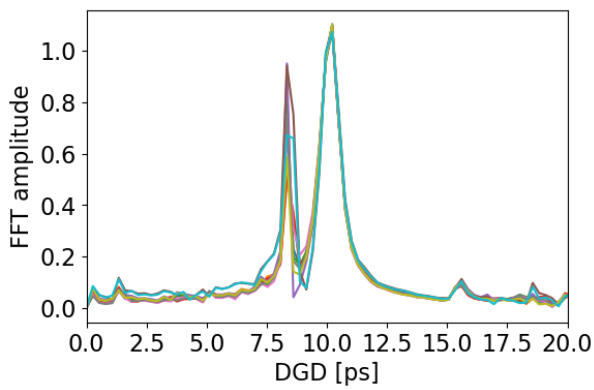


(a)



(b)

Fig. 4: (a) Measured loss spectra for 4 m TMSIF spliced to SSMF with offset splices for 10 different input polarizations. (b) Fourier transform of spectra of figure 4a.

and the power in the fundamental mode in dB, can be found from the peak-peak amplitude of the beat pattern ([7] eq. (12)) and is found to be -34 dB. The peak-peak amplitude of the measurement of figure 3a is found as the difference of the maximum loss for all wavelengths and polarizations and the minimum loss for all wavelengths and polarizations. Further insight is gained by Fourier transforming the loss spectra as shown in figure 3b. From simulations with a mode solver on the refractive index profile of the fiber, the peak in figure 3b at a differential group delay (DGD) of 8.3 ps is identified as originating from beating between the LP_{01} and the LP_{11} mode and the peak at 10.0 ps is found to originate from beating between LP_{01} and LP_{02}. For the case of optimal splices and no mode strippers shown in figure 3, a quite low polarization dependence is observed. It should be noted that beating between LP_{01} and the LP_{21}, which should happen for a DGD of 16 ps, is not observed

To find the optimum mode stripper configuration, the TMSIF to SSMF splices are replaced with splices with an intentional offset and made with standard splice parameters on an arc fusion splicer. Measured loss and Fourier transform of the measurements are shown in figure 4. The total MPI is then increased to -13 dB. From the Fourier transforms in figure 4b, it can be concluded that both LP_{11} and LP_{02} is launched. Compared to the optimal splices, an increased polarization dependency is also observed. From the Fourier transform in figure 4b it can be seen that it is the peak at a DGD 8.3 ps, corresponding the coupling between LP_{01} and LP_{11}, which is polarization dependent. Different bend diameters (16, 12.5, and 11 mm) and number of coils are now tested to obtain max suppression of the higher order modes and minimum extra loss for the fundamental mode. The optimum is found to be two perpendicular bends consisting each of two turns around a 12.5 mm mandrel, which suppress the total MPI to -30 dB, with an added loss for the LP_{01} mode of only 0.1 dB. The need for two perpendicular bends was confirmed by using 2 turns in only one direction, which gave a higher total MPI of -18 dB. Increasing to 4 turns in one direction only decreased the MPI to -19 dB. Using optimum splices and the optimum mode stripper of two perpendicular bends consisting each of two turns around a 12.5 mm mandrel at both the input an output splice gave a total MPI of -41 dB. Finally, the TMSIF was cut between the mode strippers and 5 m of MMF was spliced in. The result was a MPI of -34 dB and a total insertion loss of 0.67 dB. These results are for clarity summarized in table III.

TABLE III: Overview different configurations

Configuration	MPI, dB	Loss, dB
Offset splices no MS	-13	2.9
Offset splices MS 2x2ø12.5 mm	-30	3.0
Offset splices MS 1x2ø12.5 mm	-18	3.0
Offset splices MS 1x4ø12.5 mm	-19	3.0
Optimum splices no MS	-34	0.36
Optimum splices MS 2x2ø12.5 mm in and out	-41	0.63
Optimum splices MS 2x2ø12.5 mm in and out and 5 m MMF spliced in	-34	0.67

III. Link and transmission

For the transmission experiment a bidirectional link as shown in figure 5 was build consisting of a spool of 1600 m MMF in one direction and two spools with lengths of 825 and 890 m spliced together in the other direction. The spools were spliced in between the TMSIF's of the developed fundamental mode launch. The splices between the TMSIF and the MMF and MMF to MMF were done using a standard multimode program on an arch fusion splicer. All splices were protected with standard heat shrinkable splice protections sleeves. Minor to no impact on the MPI was observed due to the splice protectors. The SSMF fiber of the fundamental mode launch was equipped with dual LC connectors for easy connection to the transceivers. The MPI of the link was measured using the technique described in the previous section. The MPI and insertion loss of the 1600 m section was measured to -27 dB and 1.3 dB. For the 825+890 m section, the same figures were -18 dB and 1.4 dB. The reason for the higher MPI for the 825+890 m link gets clear when studying on the Fourier transform of the loss spectrum. Figure 6 show Fourier transforms of the loss measurements for a single polarization. For the 1600 m link distinct peaks are observed due to beating between the splices, whereas for the 825+890 m link a distributed beating is observed, which shows the presence of

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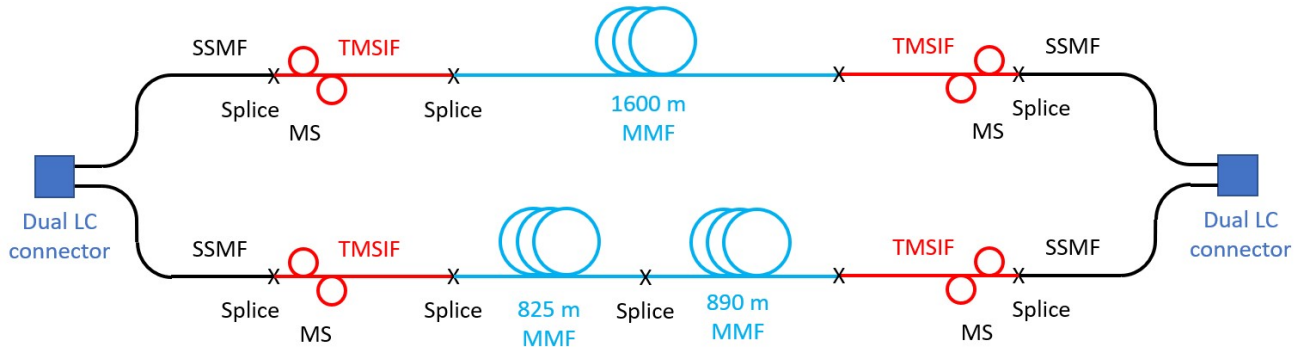
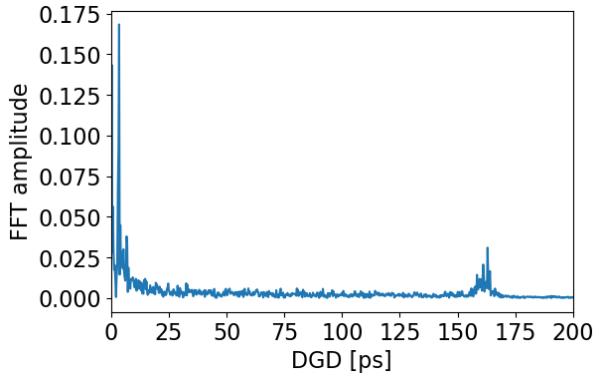
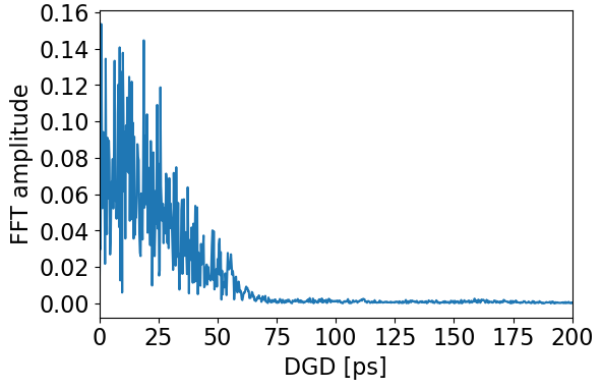


Fig. 5: Link configuration

distributed mode coupling. This is explained by the fact that the 1600 m spool was spooled by the manufacture, while the two spools of the 825+890 m link had been re-winded using a laboratory re-winder, with a poor winding quality. This is also seen on the loss for the fundamental mode at 1310 nm measured with an OTDR, where the 1600 m spool had a loss of 0.39 dB/km, while the 825 and 850 m spools had increased losses of 0.52 and 0.57 dB/km.



(a)



(b)

Fig. 6: Fourier transform of measured loss spectrum for a) 1600 m link, b) 825+890 m link.

The link was mounted between two NVIDIA Mellanox 100 GbE QSFP28 CWDM4 Optical Transceivers mounted in a Xena Networks Ethernet tester. The link was kept running for 16 days without detection of any faulty Ethernet package in any direction.

IV. Conclusion

A simple converter from a transceiver singlemode input/output to the fundamental mode of a 50/125 µm (OM2/3/4 or 5) multimode fiber based on a four mode intermediate fiber is reported. The added loss from the two converters on input and output is only 0.7 dB, which is believed to be record low. The coupling to the fundamental mode is very efficient with a multi path interference (MPI) of only -34 dB. Compared to previous suggested solutions, no free space parts or mechanical connections are used resulting in better long term stability. The converter was tested in a 100 GbE link of 1.6 km in one direction and 1.7 km in the other direction using standard commercial transceivers. In the 1.7 km direction there was considerable extra MPI from distributed mode coupling, nevertheless, the link was kept running for 16 days without detecting any faulty Ethernet package.

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