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10 Gbit/s mode-multiplexed QPSK transmission using MDM-to-MFDM based single coherent receiver for intra- and inter data center networking

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ABSTRACT

Generalized few-mode-fiber (FMF) transmission uses N coherent receivers for mode detection, where N scales with the number of fiber modes. Multiple coherent receivers increase the cost of optical network units (ONUs) in access networks, specifically for intra- and inter data center applications. We have experimentally evaluated a cost effective low-complexity receiver architecture based on mode-division multiplexing (MDM) to mode frequency-division multiplexing (MFDM) conversion for data center connectivity. A single coherent receiver is used to efficiently detect 10 Gbit/s QPSK Nyquist signals over 2.8 km 4-LP mode graded index fiber reducing the ONUs complexity to $N/4$. All the transmitted modes are successfully detected below the forward-error-correction (FEC) limit, i.e. 1×10^{-3} BER.

1. Introduction

Since the capacity of optical fiber communication systems based on single mode fiber (SMF) is approaching the non-linear Shannon limit, researchers are paying attention to explore new paradigms including advanced coherent modulation formats, multiplexing techniques and specialized fibers [1]. While the use of classical SMF is economical but on the other hand intra-, inter-channel fiber non-linearities (optical Kerr effects) and their inter-play with differential mode group delay (DMDG) still remain the vital performance degrader in high speed conventional coherent systems. Digital signal processing (DSP) based non-linear equalization has been proposed as potential candidate to overcome the physical limitations imposed by the fiber channel. But the computational efforts, in terms of number of complex multipliers and required number of samples to encompass the optical channel memory, need to be simplified. As far as, the required DSP resources are concerned, real-time hardware demonstration of these non-linear equalizers is not yet foreseen in the near future due to the high complexity logic.

Spatial Division Multiplexing (SDM) [2] has been investigated as an alternative approach that has recently being advanced by the research community, albeit being proposed many years ago in the form of multi-mode fiber transmission [3]. The use of multi-core fibers (MCFs) and few-mode fibers (FMFs) can substantially increase the transmission capacity per optical fiber beyond the non-linear Shannon limit of SMF systems by offering parallel paths for data communication [4–6]. The transmission through MCF is considered as a smooth transition from SMF due to the fact that off-the-shelf transceivers and devices can be used for its implementation [7]. Whereas, FMF based transmission not only needs specialized multiplexers and demultiplexers [8] but also phase plates or spatial light modulators (SLMs) for generating the respective modes. These spatial modes generally exhibit DMGD and differential modal loss/gain. To mitigate these linear impairments, equalization by multiple-input multiple-output (MIMO) DSP is required at receiver. Furthermore, the number of coherent receivers required for efficiently detect the linearly polarized (LP) modes are directly proportional to the number of modes transmitted in the fiber, as shown in Fig. 1(a). In addition to the increase in receiver system complexity, the conventional coherent scheme requires tight skew adjustments among all the received modes after fiber propagation to effectively equalize the received signals by adaptive MIMO DSP algorithms [9,10]. Moreover, the DSP complexity of the classical coherent processing is high, i.e. for LP_{01}, $LP_{11_{a,b}}$, $LP_{21_{a,b}}$ and LP_{02} modes we have to implement 2×2, 4×4, 4×4, and 2×2 MIMO blocks,

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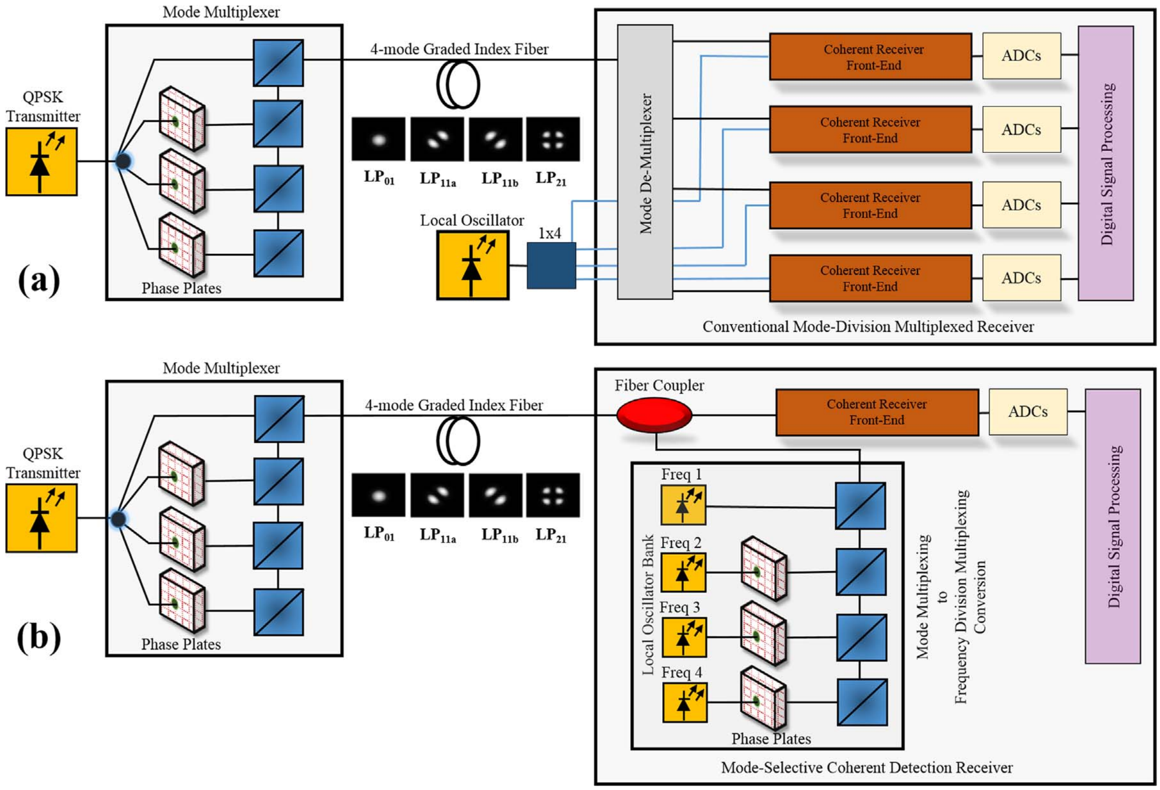

Fig. 1. Schematic and complexity comparison of: (a) conventional mode division multiplexed coherent transmission and (b) mode division multiplexed transmission based on frequency division multiplexed receiver.

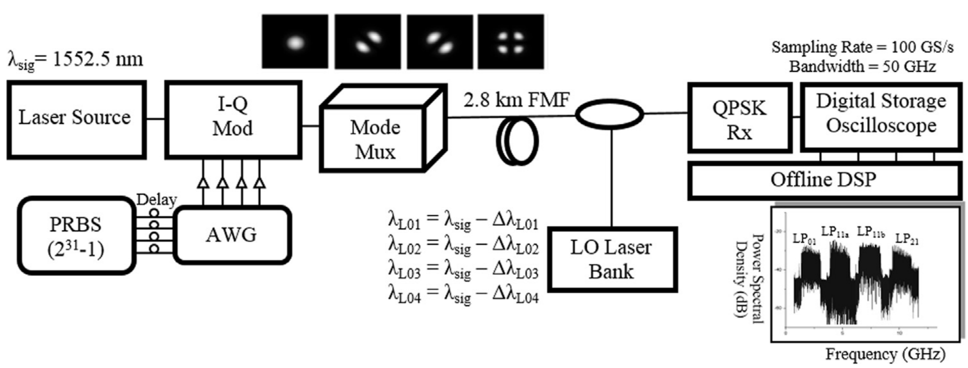

Fig. 2. Experimental setup for 2.5 Gbit/s/mode (aggregate 10 Gbit/s) transmission over 2.8 km 4-LP mode graded index fiber with mode frequency division multiplexed based coherent detection scheme.

respectively. Collectively, the receiver architecture including DSP is power hungry. This characteristic of FMF based network made it effectively expensive that is impractical for access and data center applications. Most recently, all-optical fiber based mode selective photonic lanterns have been demonstrated for reducing the complexity of MIMO processing [11]. The limitation of this device is that they are not flexible in terms of scalability and adaptability. Furthermore, the performance of photonic lantern is immensely dependent on the fabrication process [12]. On the other hand, DSP based mode selective receivers have been successfully demonstrated [13,14] but the studies are only limited to back-to-back system configurations. Most recently, advancements have been made to remove the capacity crunch at the access networking level [15] via coherent receiver implementation [16,17] and in data networking architectures [18] through space division multiplexing. However, the complexity of receiver architecture especially for the FMF transmission is still unreasonable for cost-effective implementation of high bandwidth services.

In this paper, for the first time to the best of our knowledge, we have experimentally validated the transmission of 4-LP modes in 2.8 km of graded index fiber at the data rate of 10 Gbit/s by modulating QPSK Nyquist signals and mode selective receiver, as shown in Fig. 1(b). All the LP modes are successfully received via one coherent receiver based on cost effective low-complexity architecture, i.e. MDM to MFDM conversion. The single polarization diversity heterodyne receiver with 4×4 MIMO equalization is employed. The transmission performance is further validated in-terms of bit-error-rate (BER) at diverse wavelengths to emulate the bi-directional traffic, i.e. uplink and downlink. Furthermore, the system performance w.r.t the transmission distance is analytically investigated under practical operating conditions. These results are helpful for the future implementation of SDM-FMF at intra- and inter data center networking level where cost vs. performance in an important parameter.

2. Experimental setup

Fig. 2 depicts the experimental setup of 4-LP mode transmission