

# 1 Tbit/s/ $\lambda$ Transmission Over a 130 km Link Consisting of Graded-Index 50 $\mu$ m Core Multi-Mode Fiber and 6LP Few-Mode Fiber

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**Abstract** We demonstrate 1 Tbit/s/ $\lambda$  single-span transmission over a heterogeneous link consisting of graded-index 50  $\mu$ m core multi-mode fiber and 6LP few-mode fiber using a Kramers-Kronig receiver structure. Furthermore, the link budget increase by transmitting only three modes while employing more than three receivers is investigated.

## Introduction

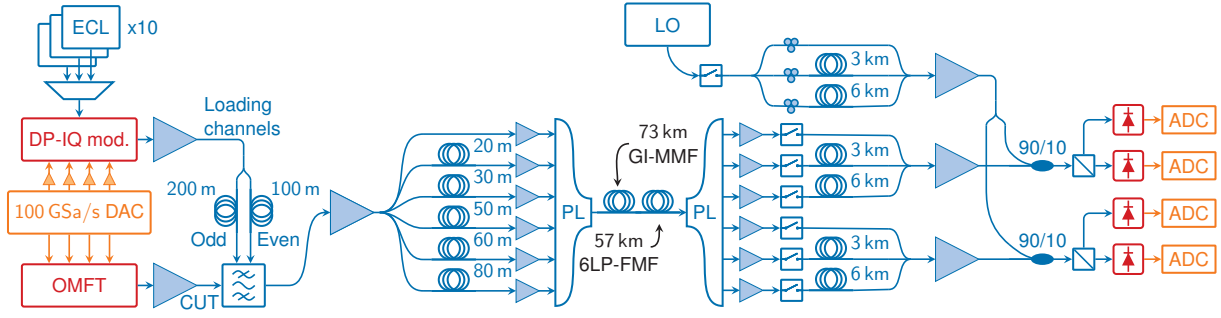
As the bandwidth requirements in various parts of optical networks rapidly approach the limits of single-mode fiber (SMF), research towards overcoming these limitations intensifies. Space-division multiplexing (SDM), where data is transmitted over multiple modes and/or cores in a single fiber, has been shown as a promising candidate to overcome the SMF capacity limits<sup>[1]</sup>. It is expected that the first SDM deployments will be for applications requiring high-capacity short-reach interconnects, such as for inter-data center connections, 5G front/back-hauling and high capacity access links. However, due to the cost sensitivity of transceivers in these types of optical systems, complex and costly systems are prohibitive. The Kramers-Kronig (KK) receiver architecture is a potential candidate to reduce hardware complexity and its related costs. This detection method allows the recovery of the full complex field, similar to intradyne coherent detection, with a single photodiode and without the optical hybrid<sup>[2]</sup>. This KK receiver has been proven to be compatible with polarization-<sup>[2],[3]</sup> and space-division multiplexing<sup>[4],[5]</sup>. While research towards SDM continues at a rapid pace, it has yet to be decided which fiber technology will be dominant in future optical transmission systems. Few-mode, multi-mode, and multi-core fibers each have their own advantages and disadvantages. Separation of spatial channels in multi-core fiber (MCF) is easier compared to coupled-core fiber (CCF), few-mode fiber (FMF) or multi-mode fiber (MMF), however, MCF manufacturing is more challeng-

ing. FMF and MMF on the other hand, potentially offer the highest capacity density, but heavily rely on complex digital signal processing (DSP) to recover the spatial channels. As operators are expected to install different fiber types in future networks, a heterogeneous optical connection might be unavoidable<sup>[6]</sup>.

In this work, we investigate a heterogeneous single-span link of 130 km comprising of 73 km of 50  $\mu$ m core diameter MMF (supporting up to 45 modes) and a 57 km of 28  $\mu$ m core diameter 6-LP FMF (supporting up to 10 modes). A net transmission rate of 1 Tbit/s/ $\lambda$  was achieved by multiplexing over 12 spatial channels (6 modes, 2 polarizations). Furthermore, we investigate the link budget increase by transmitting 3 modes while employing 4, 5, or 6 receivers. A 4 dBm launch power reduction was achieved by employing one additional receiver. Alternatively, an increase of up to 0.75 in generalized mutual information (GMI) can be achieved by activating all 6 receivers at the same transmitted power.

## Experimental setup

The employed experimental setup is shown in Fig. 1. Pseudorandom bit sequences (PRBSs) containing  $2^{16}$  polarization-multiplexed 8-ary quadrature amplitude modulation (PM-8QAM) symbols are generated offline at 33.33 GBd, oversampled to 3 samples per symbol, pulse shaped using a root-raised-cosine (RRC) filter with a roll-off of 1 % and pre-emphasized for transmitter bandwidth limitations. The resulting samples are uploaded to a 100 GSa/s digital-to-analog converter (DAC). An optical multi-format trans-

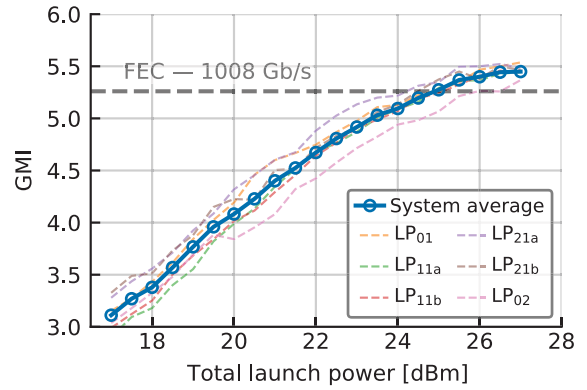


**Fig. 1:** Experimental setup for transmission over 6 spatial modes. A CUT is modulated together with 10 loading channels and is transmitted over 130 km of multi-mode fiber. At the receiver side, a TDM-SDM scheme together with KK receivers is used to reduce the receiver complexity. For transmission over only 3 modes, only the first 3 EDFAs connected to the PL are enabled.

mitter (OMFT), which contains RF-amplifiers, a dual-polarization IQ-modulator (DP-IQM), an automatic bias controller and an external cavity laser (ECL) with a 100 kHz linewidth is connected to the positive differential DAC outputs to provide the channel under test (CUT) at 193.4 THz. The negative differential DAC outputs are amplified and used to modulate 10 tones generated by ECLs to provide the loading channels. The loading channels are subsequently amplified and decorrelated by splitting them, delaying them using fibers of 100 m and 200 m. The loading channels are multiplexed around the CUT on a 50 GHz wavelength-division multiplexing (WDM) grid using an optical tunable filter (OTF) which is configured such that from the 100 m path only the even channels pass and from the 200 m path only the odd channels.

The resulting signal is amplified, split into 6 paths with lengths 0 m, 20 m, 30 m, 50 m, 60 m and 80 m to decorrelate the tributaries. Next, the tributaries are amplified and fed into the  $LP_{01}$ ,  $LP_{11a}$ ,  $LP_{11b}$ ,  $LP_{21a}$ ,  $LP_{21b}$ , and  $LP_{02}$  ports of a 6-mode photonic lantern (PL)<sup>[7]</sup>. Disabling the erbium-doped fiber amplifiers (EDFAs) of the three highest modes allows switching between 3-mode and 6-mode transmission. The output of the PL is transmitted over a link consisting of 73 km of 50  $\mu$ m core diameter MMF<sup>[8]</sup> and 57 km of 6-LP FMF<sup>[9]</sup>. In order to transition effectively from the 4-LP FMF attached to the PL to the large core diameter MMF, an intermediate 6-LP FMF is fusion spliced in between the PL and the MMF and functions as a mode adapter.

At the receive side, the spatial channels are demultiplexed using a PL of which the single-mode ends are fed into two time-domain multiplexed space-division multiplexing (TDM-SDM)<sup>[10]</sup> stages, which are connected to two polarization-diverse KK receivers<sup>[2]</sup> with a 18.5 GHz local os-

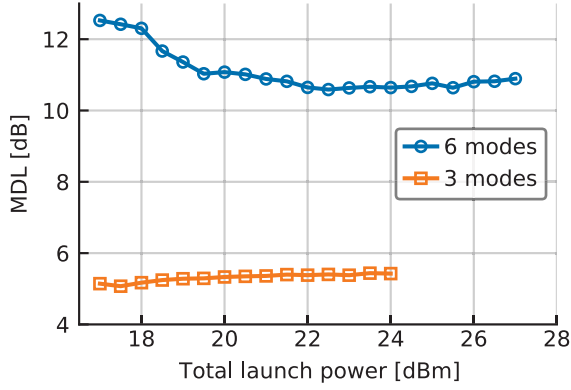


**Fig. 2:** GMI versus total launch power for 6 mode transmission, showing 1008 Gbit/s/ $\lambda$  net data rate. Dashed lines show the GMI for individual modes.

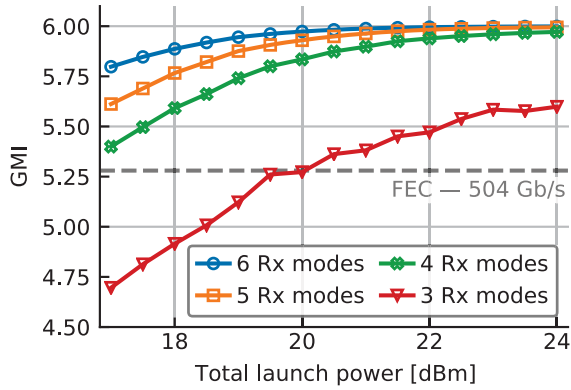
cillator (LO) offset. This reduces the required amount of analog-to-digital converters (ADCs) from 24 to 4 for this scenario. The resulting signals are digitized by a 4-channel 80 GSa/s ADC with 36 GHz of analog bandwidth, and the TDM-SDM signals are parallelized. The DC bias needed for AC-coupled KK receivers is optimized<sup>[11]</sup>, after which the KK algorithm is performed. The residual frequency offset is estimated and compensated for, the signal is RRC filtered, and decision-directed multiple-input multiple-output (MIMO) equalization with in-loop blind-phase search is applied. Finally, GMI evaluation is performed and averaged over 5 captures containing 241 000 symbols per mode.

## Results and discussion

In Fig. 2, the GMI per mode of the CUT is shown for the 6-mode transmission setup, indicating the system performance. In order to obtain error free transmission after forward error correction (FEC), a FEC scheme employing a spatially-coupled low-density parity-check (LDPC) combined with an outer hard-decision Bose-Chaudhuri-Hocquenghem (BCH) code is assumed, resulting in a normalized GMI limit of 0.8798 with a code rate of 0.8402 (19% over-



**Fig. 3:** MDL derived from the equalizer taps for the 6-mode and 3-mode transmission system.

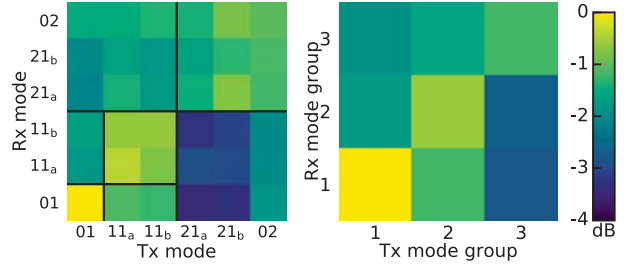


**Fig. 4:** GMI versus total launch power for 3 mode transmission, showing 504 Gbit/s/ $\lambda$  net data rate. By activating extra receivers, the link budget can be increased.

head)<sup>[3]</sup>. Combining this with the line rate of 1200 Gbit/s/ $\lambda$ , a net data rate of 1008 Gbit/s/ $\lambda$  is achieved. Furthermore, the mode-dependent loss (MDL), given as the ratio between the maximum and minimum of the frequency-averaged eigenvalues of the channel transfer matrix, is given in Fig. 3. Here, the transfer matrix is obtained from the MIMO equalizer. A mode-dependent loss (MDL) of 11 dB can be observed for launch powers achieving the FEC limit.

Next to the 6-mode transmission case, also a 3-mode transmission experiment is performed. At the transmitter, EDFAs connected to the LP<sub>21</sub> and LP<sub>02</sub> ports of the lantern are disabled, resulting in transmitting only the LP<sub>01</sub> and LP<sub>11</sub> modes. For decoding at the receiver, out of the six received modes only the lower three modes are used for this transmission case. The resulting GMI per mode is depicted by the red curve in Fig. 4, achieving a line rate of 600 Gbit/s/ $\lambda$  and a net data rate of 508 Gbit/s/ $\lambda$ , assuming the same FEC scheme as for the 6-mode transmission. From Fig. 3, it is seen that the system MDL is reduced compared to the 6-mode transmission system, to about 5.5 dB.

Fig. 5 shows transfer matrix of the 6-mode



**Fig. 5:** Transfer matrix at receiver, showing the polarization averaged (left) and the mode group averaged transmission (right), indicating strong crosstalk between the mode groups

system after 130 km. The absolute values of the time-domain taps of the MIMO equalizer are summed per input/output combination and subsequently squared and averaged over polarizations. To obtain the mode group averaged transfer matrix shown in Fig. 5, the average transmission within a mode group is taken. From Fig. 5, it is seen that there is a relatively large coupling between the modes, especially between the transmitted LP<sub>01</sub>, LP<sub>11a</sub>, and LP<sub>11b</sub> modes and the third mode group. This third mode group is not used for the 3-mode transmission system, so performance could be increased when also capturing information in these higher order modes.

Therefore, the 3-mode transmission experiment is repeated, but up to 6 received modes are used at the receiver. From Fig. 4 it is seen that by activating extra receivers, the GMI is increased with up to 0.75 at low launch powers due to added diversity. On the other hand, a reduction of approximately 4 dB in launch power can be achieved.

## Conclusions

1 Tbit/s/ $\lambda$  SDM single-span transmission using 12 spatial channels (6 modes, 2 polarizations) over a 130 km link consisting of 73 km 50  $\mu$ m core diameter MMF and 57 km of 6-LP FMF is demonstrated. Transmitting using only the first 2 mode groups yields a 500 Gbit/s/ $\lambda$  net data rate. By increasing the number of received modes, the link budget is increased, allowing reduction in launch power or increase in GMI. It is expected that heterogeneous fiber links will be employed for high-capacity short-reach transmission.

## Acknowledgements

This work was partially funded by the Dutch NWO Gravitation Program on Research Center for Integrated Nanophotonics (Ga 024.002.033) and by the TU/e-KPN Smart Two project. Fraunhofer HHI and ID Photonics are acknowledged for providing the Optical-Multi-Format Transmitter.

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