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400 Mbit/s (2×200 Mbit/s) 2-channel multiple input multiple output (MIMO) transmission over a 50 μm core multimode fiber

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The possibility of using MIMO (multiple input multiple output) technique, which is well-known from radio communications, has been experimentally shown at the optical domain. A successful 2-channel transmission beyond the baseband of 4.4 km long OM2 grade 50 μm core multimode (MM) fiber has been demonstrated. Total throughput of 400 Mbit/s has been obtained. Incoherent detection of the light signals at the receiver has been used.

Keywords: incoherent optical MIMO transmission, multimode fiber, transmission beyond the baseband.

1. Introduction

The MIMO technique, which is well-known from wireless transmission (it is a part of such standards like: 802.11n, 4G, 3GPP, LTE, WiMax), has also been applied in the optical fiber communications. One example are systems that employ a few mode or multicore fibers [1]. Considerable grow transmission capacity of a medium is obtained in this case. But at the beginning this technique was used in typical multimode (MM) fibers [2]. There are two versions of the latter technique: using incoherent detection [1] and coherent one (COMIMO) [3]. The coherent technique is complicated and costly so we have concentrated on the incoherent transmission. The low cost and relatively simple construction of the system are very important in the context of one of its main potential applications, *i.e.*, used to expand the scope and coverage of wireless local networks. There is a big chance that constructing such hybrid solutions will allow in the near future to solve problems with a relatively small range of these networks, radio signals interference, and distribute signals to places where today it is very difficult or even impossible to provide them in the wireless form.

The latter technique makes use of the analogy between multipath propagation known in radio systems and intermodal dispersion characteristics for MM fibers, see Fig. 1.

What is important, the dispersion is used here to obtain the decorrelation of signals transmitted in separate channels. It means that the intermodal dispersion does not limit

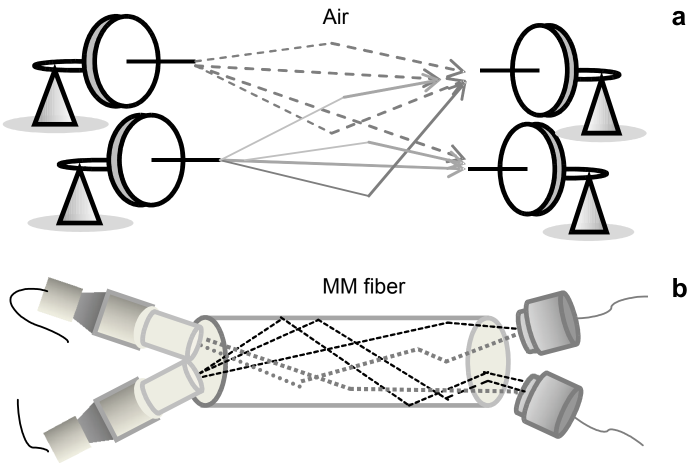

Fig. 1. Analogy between a phenomenon of signal multipath in radio transmission (**a**) and intermodal dispersion in MM fiber (**b**).

a modulation rate but is also indispensable for the system operation itself. However, the bit rates obtained so far with this technique have not been impressive (a few tens of megabit per second at maximum) [3, 4]. Here we present a successful transmission of two 200 Mbit/s MIMO channels (total throughput of 400 Mbit/s) beyond the baseband of OM2 grade MM fiber (core diameter 50 μm), which was 4.4 km long.

2. Theory

The schema of the incoherent fiber system over MM fiber was described for the first time in [3]. The construction of such system assumes that N identical RF carriers are modulated with separate digital data streams and these signals individually drive N laser transmitters, whose light is combined by a coupler/splitter and launched into a MM fiber. At the receiver side, the light is split into M ($M \geq N$) optical paths (by a second splitter), detected, and then processed electronically. Each of the transmitting lasers excites in the MM fiber slightly different modes or mode groups. Furthermore, both the input optical coupler and the output optical splitter have mode selective properties (*i.e.*, to some extent they filter modes/mode groups). Therefore, each connection between i-th receiver and j-th transmitter is realized by different modes. To better understand a nature of such systems, let us write the relation between N input signals $[s_1 ... s_N]^T$ and corresponding to them M output signals $[r_1 ... r_M]^T$. For simplicity, we assume that the number of receivers equals the number of transmitters $[r_1 ... r_N]^T$. Hence, we can write the following relation:

$$[r_i] = [h_{ij}] \cdot [s_j] \tag{1}$$

where $[h_{ij}]$ is the transmission matrix containing the transfer functions between all receiver/transmitter pairs, what is expressed by the following equation:

$$[h_{ij}] = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1M} \\ h_{21} & h_{22} & \dots & h_{2M} \\ \dots & \dots & \dots & \dots \\ h_{M1} & h_{M2} & \dots & h_{MM} \end{bmatrix} \tag{2}$$

All matrix elements are complex numbers as they take into account both the attenuation and the phase shift of the RF carrier between i-th receiver and j-th transmitter. Each element h_{ij} can be interpreted as a superposition of influences phenomena of the modal dispersion and the chromatic dispersion. It is quite clear that by inverting the matrix $[h_{ij}]$ we may recover the original signals [5]

$$[s_j] = [h_{ij}]^{-1}\cdot[r_i] \tag{3}$$

Obviously, the matrix $[h_{ij}]$ may not be singular and its numerical conditioning determines the values of the channel SNR [6]. The matrix $[h_{ij}]^{-1}$ may be found directly by some optimization algorithm or calculated at the system initialization stage. In practice, the last one is mostly used. Because in the process of recovering signals on the receiver side, the knowledge about the inverse matrix $[h_{ij}]^{-1}$ is necessary. The greater part of such system works in two phases. In the first one (an initialization step), the matrix $[h_{ij}]$ is determined; typically, for this purpose, some special pilot signals are transmitted. Based on it, the matrix $[h_{ij}]^{-1}$ is then calculated. In the second stage (a working step), information signals are send. The inverse matrix $[h_{ij}]^{-1}$ is used in a recovery process of the originally transmitted signals.

The detailed analysis, carried out in [7], has shown that the appropriate work of the incoherent optical MIMO system over the MM fiber is possible only in a range of the frequencies which lie beyond its baseband. It means that the RF carrier frequency must be greater than the value of the frequency denoted as a 3 dB drop on the frequency characteristics. Fulfilling such conditions, it is necessary to obtain enough decorrelation between transmitted signals. The transmission is not possible in the range of the baseband frequencies. It can be perceived as a big disadvantage of this approach. In reality, it is not. These systems are natural extension of the conventional systems of transmission. Also, we must remember that wireless standards typically use frequency bands from a range of microwaves. It means that their integration with optical systems, which are based on the incoherent MIMO technique without additional electrical conversion of radio carrier frequency, should be done in this frequency range.

3. Experiment

The experimental setup is shown in Fig. 2. Arbitrary wave generator (AWG) was employed as a signal source for two channels of the MIMO system. We tested BPSK

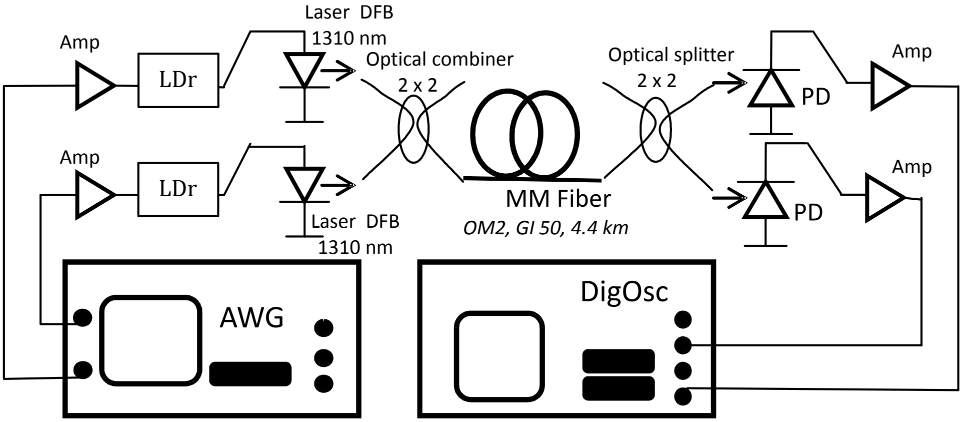

Fig. 2. Block scheme of the experimental setup.

(binary phase shift keying) modulation with 200 Mbit/s rate and the total throughput 400 Mbit/s.

The carrier frequency might be selected between 0.8 and 1.5 GHz, which was well beyond the baseband (160 MHz) of the MM fiber used (see Fig. 3 where the frequency response of the optical link used consisting of 2 couplers and the fiber is depicted, the baseband range is marked by dark colour). The choice of the carrier frequency and the modulation rate was limited by the passband of the used digital oscilloscope (2 GHz). After amplification these two signals from AWG drove two DFB lasers (Finisar, 1310 nm), which were coupled to two input ports of a 2×2 commercial coupler/splitter. One of its output port was connected to the transmission MM fiber (OM2 grade, 50 μm core, 4.4 km long, Corning Glass).

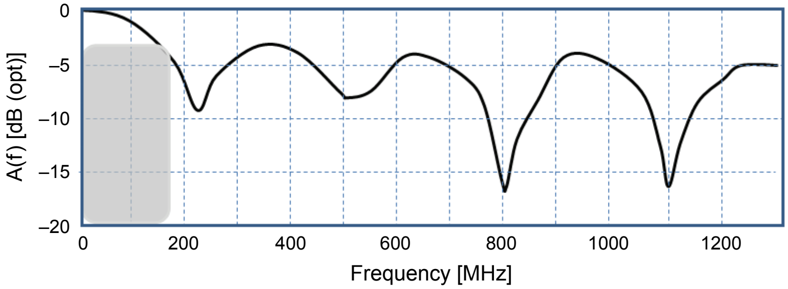

Fig. 3. Response of the link (fiber + 2 couplers/splitters) against frequency.

At the receiving node, the optical signal from the fiber was fed to an input port of the second coupler/splitter, whose outputs were connected to two *p–i–n* photodiodes (JTSU ETX-100). After pre-amplification two signals from the photodiodes were fed

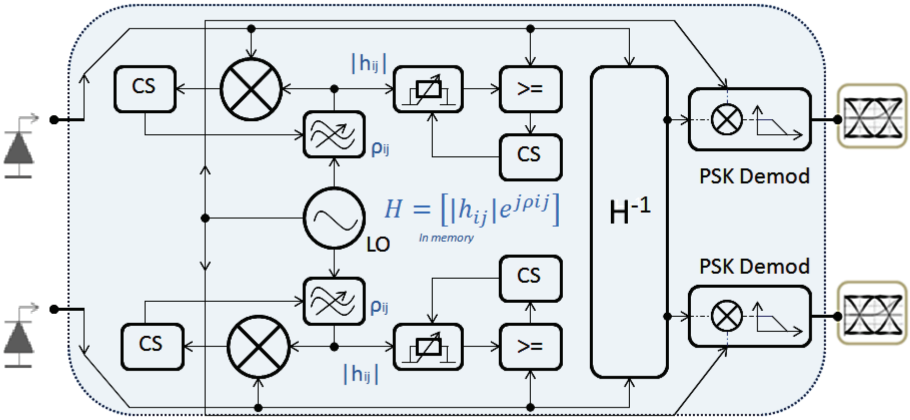

Fig. 4. Programmatic model of the MIMO receiver used in the off-line processing; CS – control system, LO – local generator, a source of referential signal.

to a digital sampling oscilloscope, where they were sampled and recorded for further (off-line) processing.

The system worked in two steps. At the first stage (initialization), no modulation was applied, and unmodulated carriers were transmitted alternatively in both channels (*i.e.*, at a given time only one channel was on sending an unmodulated carrier). The signals at both receivers were then simultaneously sampled and saved. This made it possible to determine the transfer matrix $[h_{ij}]$ in off-line post processing. After that (the second stage), an actual transmission took place with simultaneously modulated signals in both channels. Again, the signals at both receivers were recorded. During the off-line processing the inverse matrix $[h_{ij}]^{-1}$ was calculated and afterwards applied to the recorded modulated signals according to zero forcing (ZF) algorithm (Eq. (3)). Then, the eye patterns for both channels were calculated and displayed. Apart from ZF algorithm, the remaining signal processing was typical of demodulation of phase modulated signals: after hard limiting, the received signal was multiplied by the recovered carrier quadrature signals and low pass filtered. Functionality of the programmatically realized MIMO receiver was shown schematically in Fig. 4.

4. Results

Examples of the obtained eye patterns are shown in Figure 5.

The quality of the received signals was estimated based on the calculation of *Q*-parameters taken at the sampling moments. These values for different series of measurements are shown in Fig. 6.

The value of *Q*-parameter varied between 5 and 22, depending on the channel number and realization due to different cross correlations between channels. Although

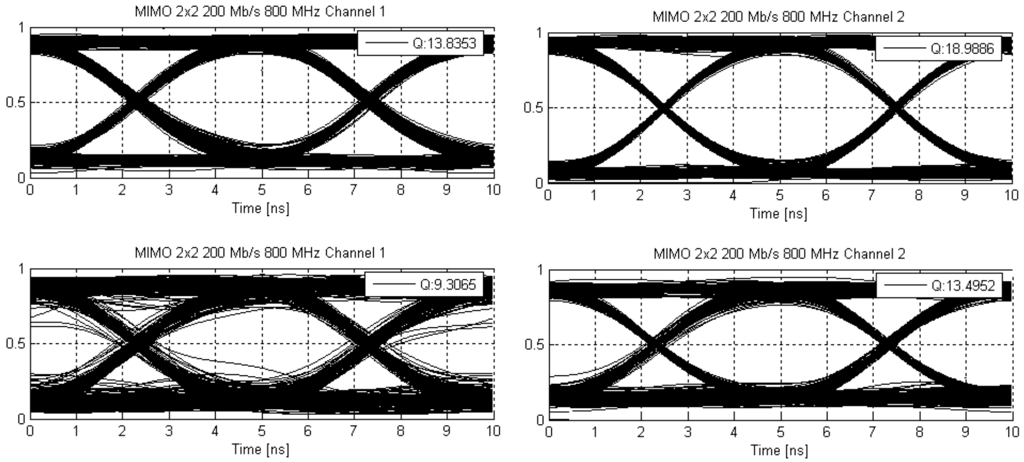

Fig. 5. Examples of the eye patterns for 2×200 Mbit/s BPSK MIMO, carrier f = 800 MHz.

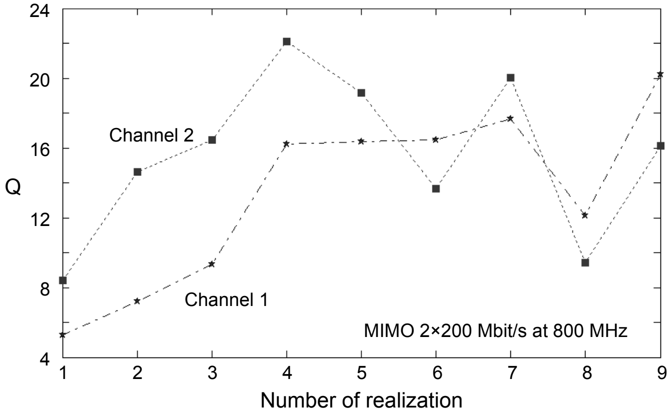

Fig. 6. Values of Q-parameter obtained for different measurements for 2×200 Mbit/s BPSK MIMO.

the signal quality was good, these results indicate that the system was not always able to meet $Q > 7$ requirement (corresponding to BER = 10^{-12}) and thus operate correctly without FEC.

5. Discussion

There are three reasons for not always sufficient value of a Q-parameter. First, in all cases matrix $[h_{ij}]$ had rather poor numerical conditioning, namely the matrix condition number varied between 6 and 10 among measurements. That meant that the system was sensitive to both the data errors and the errors of matrix coefficients. Moreover, a high condition number meant amplification of receiver noise when inverting $[h_{ij}]$ and recovering signals in each channel [6]. Second, the matrix $[h_{ij}]$ was measured at an unmodulated carrier frequency. However, the actual transmission involved modulation and the signal spectrum occupied a much wider frequency range. The $[h_{ij}]$ matrices for unmodulated and modulated signals might have differed to some extent. Third, the transfer matrices were a bit unstable over time due to the sensitivity of a mode selective element (such as couplers/splitters) to the input speckle pattern (that varied in time) [8]. That is, the matrix $[h_{ij}]$ measured before transmission, was not exactly the same as during the actual transmission. That fact, combined with poor numerical conditioning, led to errors during matrix inversion. A thorough analysis of the recovered signals proved that the errors in ZF algorithm mentioned above led to much greater amplitude than phase errors. Therefore, we employed constant envelope modulation format (BPSK) as well as signal hard limiting during the post processing.

6. Conclusions

We have demonstrated a successful 2-channel MIMO transmission over 4.4 km of typical OM2 grade 50 μm core MM fiber with a total throughput of 400 Mbit/s and BPSK modulation format. We employed the ZF algorithm for channels recovery with the accompanying measurements of the transfer matrix prior to the actual transmission. The lowest measured value of the Q-parameter was around 5, which makes this transmission feasible with some form of FEC. It is necessary to stress that better results (no FEC necessary) are expected if $[h_{ij}]$ estimation errors are reduced and better algorithms for data processing (*e.g.*, maximum likelihood or minimum mean square error) are employed.

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