30Gbit/s 3 × 3 Optical Mode Group Division Multiplexing System with Mode-Selective Spatial Filtering

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Abstract: A 30Gbit/s 3 × 3 optical Mode Group Division Multiplexing system with Mode-Selective Spatial Filtering (MSSF) using single-mode fiber is demonstrated over 20m graded-index multimode fiber. Crosstalk among the mode groups is minimized through MSSF.

OCIS codes: 060.2330 Fiber optics communication; 060.4230 Multiplexing

1. Introduction

Multimode fiber (MMF) has received much attention in short range optical communication systems due to its advantages in easier alignment and lower module assembly cost compared to single mode fiber (SMF). In local area networks (LAN), MMF is attractive for replacing copper cable (CAT-5E). For instance, the IEEE-802.3 standard includes the transmission of 10Gb/s signals over 300m OM3 MMF. To meet the demand for higher capacity, many schemes to realize high-speed transmission over MMF have been demonstrated [1,2]. Among these schemes, Mode Group Division Multiplexing (MGDM), an optical MIMO technology, has been proved as a competitive candidate [3], which utilizes different guided modes in MMF to transport different signals without the need for additional bandwidth.

In this paper, the experimental results of a 30Gbit/s 3 × 3 optical MIMO-MGDM system with Mode-Selective Spatial Filtering (MSSF) will be evaluated. MSSF is realized by using SMF. Moreover, principles of selective launching and MSSF are explained.

2. Selective Launching

A set of LP (Linearly Polarized) modes which have similar properties such as propagation constant and group delay, can be seen as one mode group. For the mode $LP_{m,n}$, the order of the mode group or mode group number p is defined as [4]:

$$p = m + 2n - 1 \tag{1}$$

where m is the azimuthal mode number and n is radial mode number.

The selective launching relies on the excitation of a subset of all guided mode groups of a MMF. The number of all guided mode groups can be calculated through the propagation constant [5]:

$$\beta_p = k_0 n_1 \left(1 - \frac{2p}{k_0 n_1}\cdot\left(\frac{2\Delta}{a^2}\right)^{\frac{1}{2}}\right)^{\frac{1}{2}} \tag{2}$$

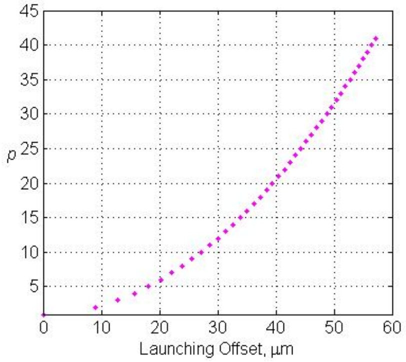


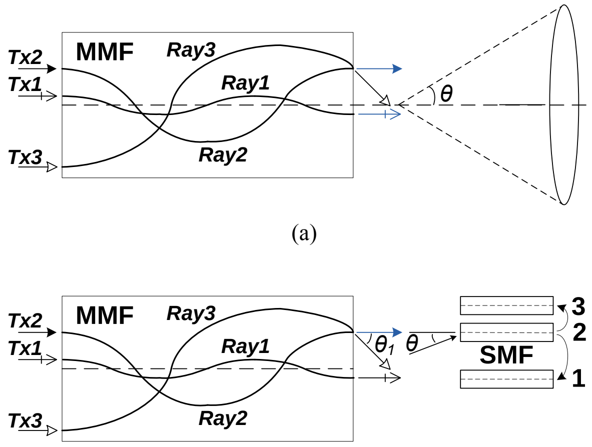
Fig. 1. The launching offset of the *pth* mode group.

where k_0 is wave number, n_1 and n_2 are the refractive indices of core and cladding respectively, a is the core radius of the MMF and relative refractive index parameter $\Delta = (n_1^2 - n_2^2)/\, 2n_1^2$. For guided modes, the propagation constant should satisfy $k_0 n_2 < \beta_p < k_0 n_1$, so all orders of guided mode groups should follow:

$$0 < p < \frac{\pi\left(n_1^2 - n_2^2\right)}{\lambda n_1}\cdot\left(\frac{a^2}{2\Delta}\right)^{\frac{1}{2}} \tag{3}$$

118 guided mode groups can propagate through a 185/250µm GI-MMF when the wavelength of the input light is λ=660nm. In principle, each of the mode groups can be utilized as a channel so multiple signals can be transmitted with the prerequisite that mode mixing is relatively low. In Fig. 1 the number of the mode group is plotted as a function of the radial launching offset. It is plotted using the approximation that the peak point of the $LP_{M,1}$ mode in the *pth* mode group ($p=M+1$) is regarded as the launching position. The mode distribution is acquired through the numerical solution of the scalar wave [6]. From Fig. 1, it can be seen that when the launching offset is larger than 20µm, even for an optical beam with a beam diameter of 10µm, at least 7 mode groups will be excited.

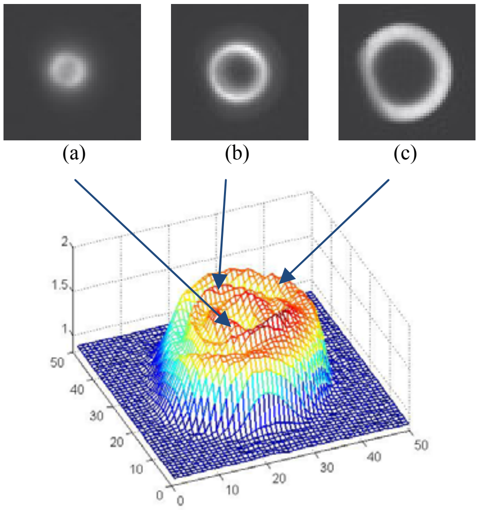
3. Mode-Selective Spatial Filtering



(a)

(b)

Fig. 2. The principle of MSSF through the use of (a) a lens with small NA and (b) a standard SMF.



(a) (b) (c)

(d)

Fig. 3. (a)-(c) NFPs with MSSF launched by different radial offset; (d) the combined intensity distribution of three mode groups.

The application of the Mode-Selective Spatial Filtering (MSSF) into MGDM systems was proposed in [7,8], where a lens with a small numerical aperture (NA) was used to mitigate the crosstalk between mode groups yielded with different radial offset, as shown in Fig. 2(a). A microscope objective lens with 5× magnification and NA=0.1 was utilized to measure the near field pattern (NFP) at the output facet of a 20m long 185/250μm GI-MMF. Fig. 3(a)-(c) give the NFPs with different radial offset launchings, at a wavelength of 660nm. It can be seen from the combined intensity distribution of the three mode groups in Fig. 3(d) that different mode groups could be detected spatially with the aid of MSSF. This NFP can be projected onto a multi-segment photo detector (PD) to realize photo-detection [8]. However, this kind of multi-segment PD is not available at present.

In our proposed 3 × 3 optical MIMO-MGDM system with MSSF, a standard SMF with a NA=0.14 replaces the lens to selectively filter the mode group, so a standard SMF-pigtailed PD can perform the MSSF function. The principle of MSSF realized by a SMF is depicted in Fig. 2(b), where three rays corresponding to different mode groups are launched by three transmitters with different radial offset. The output optical beams of the transmitters can be approximately described as Gaussian beams, so at the input facet of the MMF the angles of three rays from the MMF's axis can be regarded approximately as zero. While the ray is propagating over the MMF, the angle of the ray at the same radial offset would be similar to that at the input side. When the ray is closer to the MMF's axis, the angle is becoming larger. Therefore, only if the NA of the detector is smaller than that of the output optical ray, this ray can be filtered out. For instance, to selectively filter Ray2, the detection offset of the SMF is close to the launching offset, the detection position 2. In this case, the angle of Ray2 from the axis is minimal but the angle of Ray3 $\theta 1$ is out of the range of which the optical beam can be accepted by the SMF. Ray1 propagating on the lower order mode groups is launched with a small offset so that most of its power is around the fiber's axis. With the aid of offset detection with the SMF, crosstalk from the Ray1 can be removed, so Ray2 can be filtered out. According to the same principle, Ray1 and Ray3 can be filtered out at position 1 and 3 respectively. The MSSF characteristic of SMF can be applied in optical MIMO systems with higher dimensions.

4. Experimental Results and Discussion

The experimental setup of the 30Gbit/s 3 × 3 optical MIMO-MGDM system applying selective launching and MSSF is shown in Fig. 4(a). A laser diode operating at 1550nm wavelength launches into a Mach-Zehnder Modulator (MZM). The MZM is driven by the high speed pattern signal with a bit rate up to 10Gbit/s generated by a data pattern generator. The modulated light is amplified by an EDFA before it is split into three light beams. Due to different coupling and transmission losses of three optical beams propagating over different mode groups, power splitters with different splitting rations are utilized to control the powers of these optical beams to make them equal after selective detection. The three beams are decorrelated by transmission through fibers with different length. These fibers are connected to a Fiber Concentrator (FC). The distance between two adjacent waveguides at the concentrated side of the FC is 30μm. A 20m long 185/250μm GI-MMF is used as the MIMO transmission medium. The selective launching is indicated in Fig. 4(b). At the receiving side a SMF with a core diameter of 9μm is utilized for the MSSF of the output light from the 185/250μm GI-MMF and a computer-controlled micro-positioner is used to tune the detection position. Fig. 4(c) shows the three positions of selective detection. Because of the large

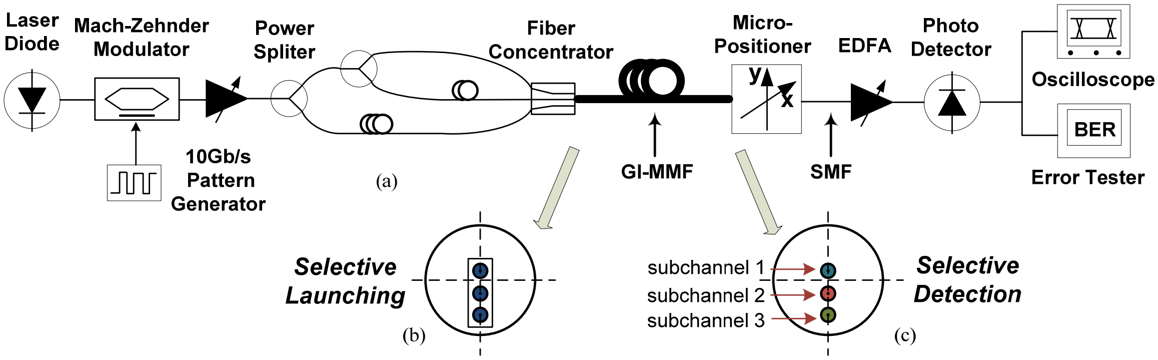


Fig. 4. (a) Experimental setup; selective (b) launching and (c) detection.

coupling loss from the MMF to the SMF, an EDFA is used to amplify the light before photo-detection. Fig. 5(a) and (b) give the eye diagrams of the three subchannels with the bit rate of 5Gbit/s and 10Gbit/s respectively. The ability of MSSF to remove the crosstalk yields a correct demodulation of the signal pattern in each subchannel, as indicated by the clearly open eye diagram. Fig. 5(c) shows Bit Error Rate (BER) curves versus different data rates for the 3 subchannels. Given that the power differences of three light beams is small, the performance of subchannel which consists of higher order mode groups is better than the performance of subchannel composed of lower order ones. The worse performance of subchannel 1 compared to other two subchannels can be explained because the interference from higher order mode groups into lower order ones is more serious than from the latter to the former; this is due to the MSSF function and the power distribution of mode groups.

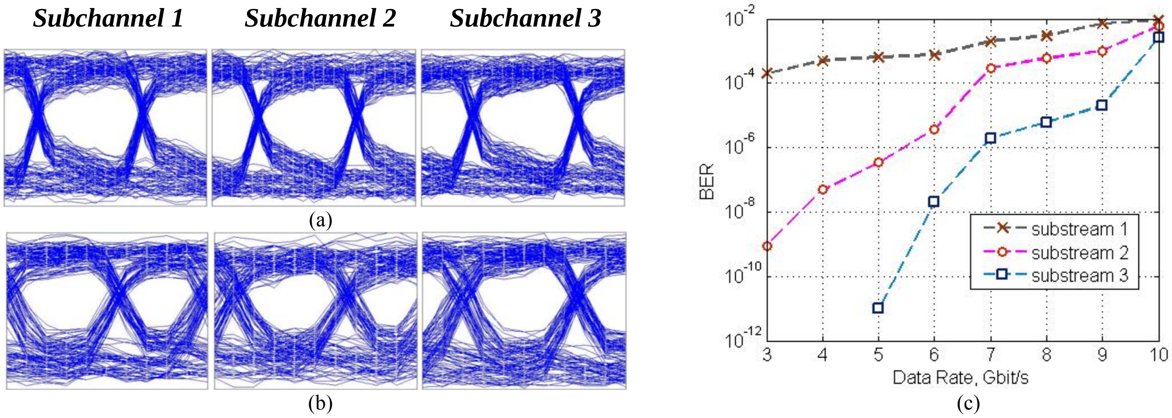


Fig. 5. The eye diagrams of the three substreams at the bit rate of (a) 5Gbit/s and (b) 10Gbit/s; (c) BER versus different data rates for the 3 subchannels.

5. Conclusion

The principles of selective launching for MGDM at the transmitter side and of mode selective spatial filtering (MSSF) at the receiver side were introduced and discussed. MSSF was applied by using a standard SMF, and enabled a 30Gbit/s 3 × 3 optical Mode Group Division Multiplexing (MGDM) system over 20m GI-MMF. The differences in performance of the sub channels for the different mode groups was proven in experiments.

Acknowledgement

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