Novel Passive Launch Scheme for Ultimate Bandwidth Improvement of Graded-Index Multimode Fibers

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Abstract: We propose a new practical multimode fiber optical launch scheme, providing near single mode group excitation for >5 times transmission bandwidth improvement. Equalization-free transmission of a 10-Gb/s signal over 220-m fiber is achieved in experimental demonstrations.

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1. Introduction

The intrinsically low operating bandwidth of multimode fiber (MMF) limits its use in high data rate transmission. Even though MMF is typically only utilized in short distance links (<500 m), high data rates of 10 Gb/s or above cannot be achieved using conventional techniques. To overcome this bandwidth limitation, various launch schemes have been studied including center launch [1], offset launch [2] and adaptive launch [3] to increase the data rate supported by MMF links. However, these restricted launch schemes cannot meet the demand for data rates higher than 10 Gb/s over a distance of 220 m, the maximum link length specified by the 10GBASE-LRM standard. However this is less than the maximum achievable capacity of a 220 m OM1 MMF link of ~38 Gb/s with a ~30 dB receiver signal-to-noise ratio and a single optical launch [4]. In this paper, we report an improved passive optical launch scheme that increases the operating channel capacity of MMF near this predicted limit. The effective modal bandwidth (EMB) achieved using the proposed launch exceeds that obtained by any passive launch scheme previously reported, and opens up a new opportunity for MMF data links by extending the achievable link length and/or increasing the attainable transmission data rate.

2. Principle of line launch

The new launch scheme, the line launch, relies on exciting only a specific mode group of the MMF at the launch, so that the pulse broadening due to the modal dispersion is minimized. This provides a maximum transmission bandwidth of a MMF towards the ultimate theoretical limit. The line launch is implemented by projecting a line of spots with a specific transverse electric field profile onto the fiber facet at the center of its core. The illumination pattern is chosen so that the line launch excites primarily the targeted mode group and not the neighboring unwanted mode groups. By suppressing the power contribution from these unwanted mode groups, an enhancement of the transmission bandwidth results.

Standard data-communication grade MMF typically has a near parabolic ($\alpha \approx 2$) refractive index profile and a relative core-cladding refractive index difference much smaller than unity ($\Delta << 1$). Under these conditions, linearly polarized modes may be assumed in solving the scalar wave equation of a radially symmetric fiber, and the transverse fields are represented to a good approximation by Laguerre-Gaussian functions, which can be expressed in terms of a Hermite polynomial in Cartesian coordinates as [5]

$$L_{\mu}^{(\nu)}\left(r^{2}\right)=\frac{(-1)^{\mu}}{2^{2\mu}\mu!}\sum_{k=0}^{\mu}\frac{\mu!}{k!(\mu-k)!}H_{2k}(x)H_{2(\mu-k)}(y)$$

from which the Hermite polynomials $H_m(x)$ to be used in our discussion are defined as

$$H_{m}(x)=(-1)^{m}\exp\left(x^{2}\right)\frac{d^{m}}{dx^{m}}\left[\exp\left(-x^{2}\right)\right]=m!\sum_{k=0}^{floor\{m/2\}}(-1)^{k}\frac{(2x)^{m-2k}}{k!(m-2k)!}$$

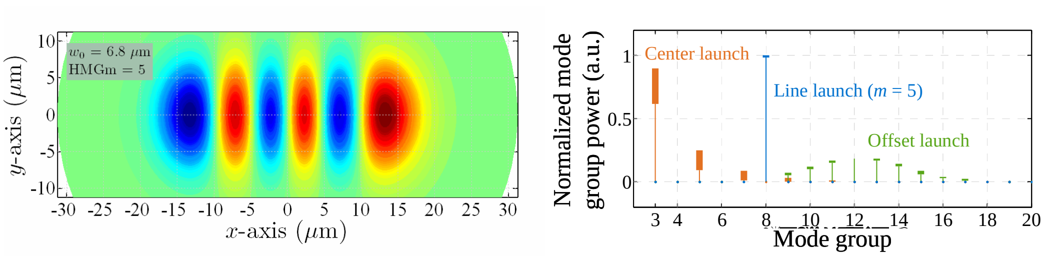
where m is the order of the Hermite polynomial and x is the displacement.

Consequently, the associated Laguerre polynomial for the basic transverse mode set for graded-index fiber can be expressed in the terms of the Hermite polynomial. For this reason, to achieve selective mode group excitation, we propose to use Hermite-Gaussian beams as a basis set for generating the launch field. We define the Hermite-Gaussian transverse electric field in Cartesian coordinates as

$$E_m(x, y, w_0) = \frac{2^{(m-1)/2}}{w_0\sqrt{\pi}\sqrt{m!}} H_m\left(\frac{\sqrt{2}x}{w_0}\right)\exp\left(-\frac{x^2+y^2}{w_0{}^2}\right)$$

where w_0 is the waist of the fundamental mode in an ideal graded-index MMF. Here, a higher order Hermite-Gaussian mode ($m > 0$) is considered in one dimension; whereas a fundamental Gaussian mode is assumed for the other dimension for the two-dimensional electric field distribution. A two-dimensional contour plot of the electric-field of a 5^{th} order ($m = 5$) Hermite-Gaussian beam is shown in Fig. 1(a) as an example. For the higher order ($m > 0$) Hermite-Gaussian beam, the different spots in a line are phase-correlated. This phase-correlation is represented with different colors in the contour plot in Fig. 1(a).

Fig. 1(b) shows the mode group power distribution of different fibers excited by a 5^{th} order Hermite-Gaussian line launch. The proposed line launch primarily excites the mid-order mode groups, which are proven to have a statistically better modal delay performance. The error bars in the plot indicate the variation of the coupled mode group power in the 108-fiber model [6]. Results for the center and offset launches are also plotted for comparison. The figure shows clearly that the line launch preferentially excites a particular mode group.



(a) (b)

Fig. 1 (a) Contour plot of the electric-field distribution of a 5^{th} order Hermite-Gaussian line launch for w_0 = 6.8 µm; (b) mode group power distribution based on 108-fiber model for OM1 fibers under 5^{th} order line launch, center launch and offset launch.

Fig. 2 plots the link yield of the calculated statistical 3 dBo bandwidth-distance products (BDPs) for different launch schemes. These statistical values are obtained by taking the expected value among the results at different launch positions under a uniform probability distribution of the launch offset for each fiber in the 108-fiber model [6]. The 80% yield for each case is indicated in the plots. A radial launch offset of ≤ 3 µm is considered in the calculations. This offset range is chosen to provide a practical alignment tolerance in the actual assembling process; and agrees with the tolerance specified for center and offset launch [7]. It can be observed that the 80% statistical yield of the BDP for line launch is at least 5 times higher than either the center or the offset launch.

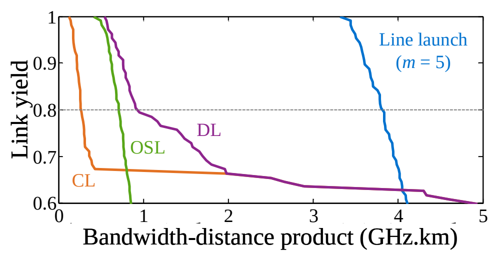
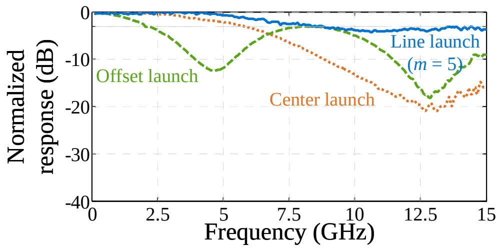


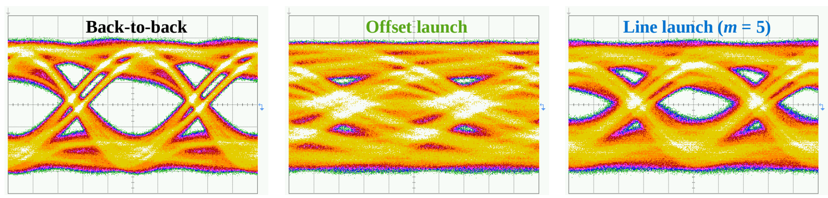
Fig. 2 Plot of the link yield of the 5^{th} order line launch, the center launch, the offset launch and the dual launch using the 108-fiber model. Results from the dual launch refer to the better bandwidth performance between the center and the offset launches for an individual fiber in the 108-fiber model.

3. Equalization-free signal transmission using line launch

We experimentally demonstrate an EMB improvement for the proposed line launch for 62.5 µm OM1 MMF through the use of a passive beam shaper, which is made with a combined phase and intensity mask, similar to the required beam profile in Fig. 1(a), on a fused silica substrate. By illuminating this beam shaper with a collimated Gaussian beam from a single-mode fiber output, a Hermite-Gaussian-like beam profile is generated for the line launch implementation. A standard mode-conditioning patchcord is used for offset launch study. The measured frequency response of the line launch under the standard 10GBASE-LRM link architecture exhibits a smooth variation over the measured frequency range with no sharp dips observed, as shown in Fig. 3(a). This smooth frequency response simplifies the complexity of any electronic dispersion compensators required for achieving overall high date rate link operation. With this high EMB and flat frequency response, we carry out an equalization-free signal transmission experiment over this 220 m sample OM1 fiber using a standard SFP+ 10.3125 Gb/s transceiver. This sample fiber is chosen to have the worst case performance in the mid-order mode group and thus to favor a center launch. Hence, this fiber is the near worst case test fiber for the new line launch. Consequently, the signal under offset launch exhibits severe inter-symbol interference. Fig. 3(b) shows the corresponding eye diagram of different signals. The un-equalized signal under line launch, unlike the offset launch condition, remains wide open and is comparable with the back-to-back case. Error-free operation is achieved for both center and line launches.



(a)



(b)

Fig. 3 Plot of (a) the measured frequency response of the 220 m OM1 sample fiber, and (b) the corresponding un-equalized eye diagrams at –10 dBm. Time base: 20 ps/div.

In the transmission experiment, a near worst case OM1 sample fiber which favors lower order mode groups (i.e. center launch) and shows a larger modal dispersion effect for the higher order mode groups (i.e. offset launch) is used to evaluate the near worst case performance of the line launch. Hence, it is possible for a single launch scheme based on a line of spots to replace the dual launch of the 10GBASE-LRM standard. This new launch also enables lower cost and lower power consumption via equalization-free signal transmission over 220 m of most industrial standard multimode fibers.

4. Conclusions

We have reported a new passive optical launch scheme over MMF for near ultimate EMB improvement. The line launch permits selective mode group excitation with high extinction ratio to the unwanted neighboring mode groups. Such unique mode group excitation leads to a smooth frequency response for the MMF link and consequently equalization-free signal transmission of 10 Gb/s signal over a 220 worst case OM1 sample fiber in a proof-of-principle demonstration. The proposed line launch scheme can be implemented with passive optical components, and hence is suitable for integration in a transceiver or in a patchcord. It is worth noting that different orders of Hermite-Gaussian beam can be used as the line launch depending on the targeted mode group to be excited.

The calculated statistical EMB is at least 5 times higher than that of the conventional center and offset launches, and is very close to the theoretical limit based on the Shannon capacity calculation. We, therefore, believe that the proposed line launch technique is the near ultimate passive optical launch solution to MMF for maximum EMB utilization.

5. References

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