Multimode Fiber Link Equalization by Mode Filtering Via a Multisegment Photodetector

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Abstract — **For short-haul optical networks, multimode fiber is ideal in regards to ease of use and cost-effectiveness. Unfortunately, modal dispersion in the fiber, can lead to severe intersymbol interference. A multisegment photodetector is used to perform spatially resolved equalization of the channel response. We demonstrate, through measured impulse response and bit error rate, robust performance to variations in channel condition.**

I. Introduction

The ease-of-use inherent to multimode fiber (MMF) has resulted in its resurgence for short haul optical access links like local area networks, intra-cabinet, and fiber-to-the-home. This is evident by the recent establishment of Gigabit and 10-Gigabit Ethernet and the provision therein for the use of MMF. Specifically, the large core and multitude of guided modes allows simple passively aligned optical coupling, resulting in easing of laser performance criteria, particularly regarding mode quality, and improved laser packaging yields. On the other hand, differential mode delay (DMD), the dispersion in group-delay among the numerous guided modes of the MMF, can lead to severe intersymbol interference. Restricted mode launch is an all optical technique that gets around the effect of DMD by limiting the number of fiber modes that are excited. Previous works [1],[2] have shown a doubling, on average, of MMF link bandwidth; however, the proposed solution negates the advantages using MMF by typically requiring an intermediate patch of single-mode fiber between the MMF and laser.

In this paper, we report the demonstration of an equalization technique that is optoelectronic in nature and maintains the benefits of MMF, while providing comparable enhancement in link bandwidth as compared to restricted mode launch. Using an overfilled launch condition, such as that resulting from a large-area, multimode vertical-cavity surface-emitting laser (VCSEL), we exploit the spatial diversity of the emitted signal at the output of the MMF with a multisegment photodetector (MSD), Fig. 1a.

The use of an MSD is analogous to the use of multiple antennas in addressing multipath fading in RF wireless link. By detecting different portions of the optical in the transverse spatial domain and subsequently recombining them with appropriate phase and amplitude weighting, we are able to reduce the effects of DMD. Most importantly, this is accomplished while maintaining all the benefits of multimode fiber including the ability to use low-cost VCSEL sources.

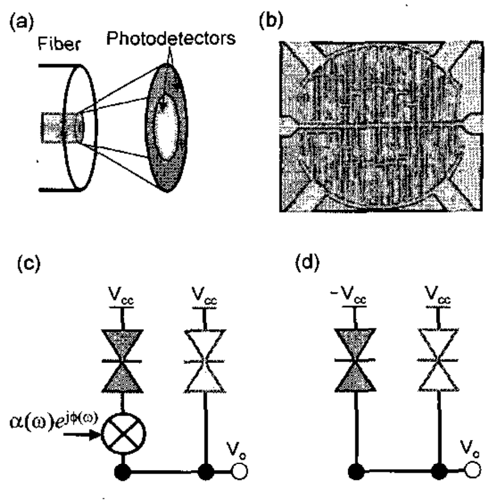

Fig. 1. (a) Spatially resolved equalization (SRE) at output of multimode fiber. (b) Micro-photograph of fabricated two-segment metal-semiconductor-metal SRE receiver. (c) Circuit of an SRE receiver using two-segment receiver and a generalized phase and amplitude adjustment. (d) Embodiment of scalar SRE resulting in a net subtraction of the segment signal.

II. Overview

While reduction of scattering mechanisms in graded-index multimode fiber (GI-MMF) has reduced the fiber loss, it has also served to minimize the coupling among the fiber modes. The consequence of this is to allow the individual modes to propagate distances in excess of 1 km without significant energy exchange, thus retaining the diversity in the temporal response among each mode.

Moreover, in GI-MMF, the guided modes of differing effective wave-vectors, β_m, also exhibit differing mode-field size. With fiber core refractive index is fabricated to the following functional form

$$n(r) \propto \sqrt{1-2\Delta\left(\frac{r}{a}\right)^{\alpha}}\,, \tag{1}$$

where r is the distance from center, α is the index profile parameter, a is the core radius and Δ is the contrast ratio in index between core and cladding. Within the span r_{span}, within the fiber over which the mode is confined the mode must satisfy $\beta_m < k_o n(r_{span})$, where k_o is the free-space wave-vector; therefore, the overall mode size will vary with β_m. Moreover, because of the monotonic relation between group-delay and β_m [3], the size of the mode-field is also monotonic function of group-delay. This results in a well behaved spatial diversity, a variation in temporal response within the emitted optical spot that can be exploited by an appropriate arrangement of multiple photodetectors (PD). This spatial diversity is demonstrated in Fig. 2. A 1-ps optical pulse is coupled into a 1.1-km GI-MMF via a mode scrambler [4], and the temporal response, as received through a 15-μm pinhole, is measured with a 2-GHz photoreceiver. The pinhole is transversely scanned 0.4 mm from the fiber.

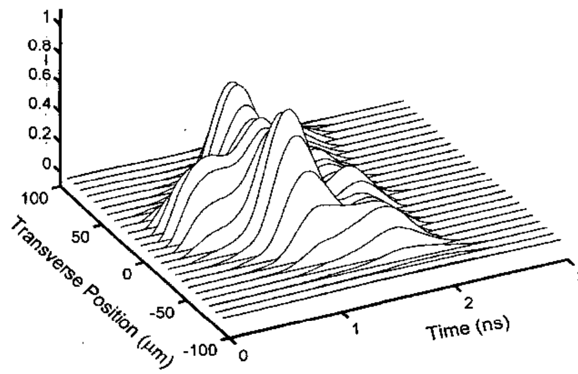

Fig. 2. Temporal signal, as received through a 15-μm pinhole, versus transverse position of optical spot, 0.4-mm from fiber end. Sample 1.1-km GI-MMF driven by 1-ps optical pulse.

The channel response is measured by transmitting a 1-ps, 1550-nm, optical pulse that is overfilled launched. A 40-GHz interleaving oscilloscope is used to measure the temporal signal from the MSD. Over a 1.1-km MMF span, the typical impulse response of the GI-MMF is 2 ns in width, which is substantially larger than that of the optical pulse or apparatus impulse response width.

Because of the bias-based approach to signal subtraction, the MSD can readily be reconfigured as a conventional PD to measure the inherent MMF impulse response; thereby providing a fair comparison of MMF link performance with and without SRE enhancement.

Various samples of both 50 and 62.5-μm core graded-index multimode fiber, all of 1.1-km length, are tested with and without spatially resolved equalization. The bandwidth of the optical fiber channel is determined by applying Fourier transform to the measured temporal response and comparison of the upper, 3-dB, cutoff frequency. Since subtraction of the two segment signal, in effect, suppresses the contribution of several fiber modes, this affects not only the width of the temporal response but also the effective pulse energy. Consequently, SRE induces a reduction in the effective detector responsivity. Because of the square-law nature of photodetection, the SRE penalty to the DC responsivity can be determined by comparing the time integral of the measured temporal responses.

We show, in Fig. 3a, the improvement in temporal response with SRE enhancement in a sample 50-μm core GI-MMF; in Fig 3b, the signals of each PD segments are shown as well, demonstrating the spatial diversity exploited by the MSD. In Fig 4, the bandwidths of the channel with and without equalization are plotted for several samples of fiber, demonstrating the robustness SRE to variation in DMD. It should be noted that the

II. Experimental Results

While maximal performance can be achieved via an MSD with complex weight factors, Fig. 1c, we demonstrate that without *a priori* knowledge of the channel, excellent performance can be attained with simple subtraction of signals from a concentric, two-segment MSD, Fig. 1d. More importantly, this embodiment can be integrated into a simple, compact photodetection device. By alternating the bias polarity between the two segments, the subtraction can be implemented within the MSD itself, without additional processing. Moreover, it can be shown that subtraction in this manner will result in a 2× improvement in signal-to-noise ratio for a thermal-noise dominated receiver.

A. Impulse Response

We have fabricated and tested a concentric MSD using a metal-semiconductor-metal (MSM) type detector on InGaAs, Fig. 1b [5]. The choice of using an MSM detector is strictly for the ease of use and fabrication. The inner segment is a disc-shaped PD with a radius of 50-μm, and the outer segment is an annular detector with an outer radius of 100-μm. The MSM has 2-μm-wide, 5-μm-pitch fingers and ~0.2 A/W responsivity.

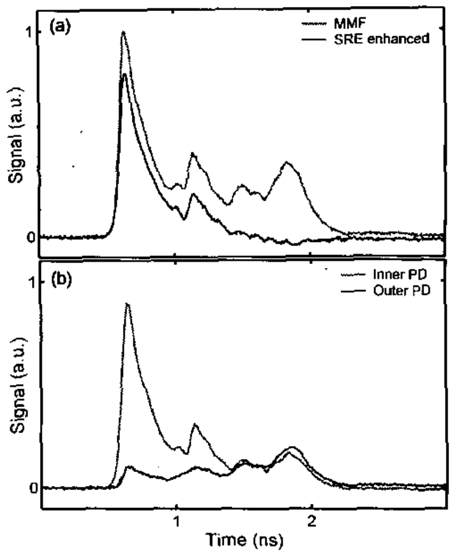

Fig. 3. (a) Measured impulse response with and without spatially resolved equalization. (b) Signal as received by each segment of the photodetector. All traces are taken with the same device under different bias conditions.

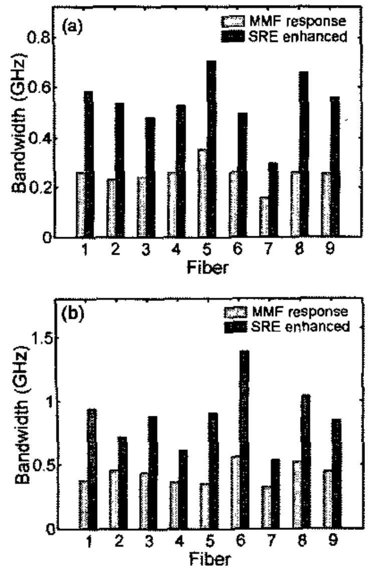

Fig. 4. Measured 3-dB bandwidth of 1.1-km graded-index MMF links with and without SRE enhancement. (a) 9 random samples of 62.5-μm diameter fiber. (b) 9 random samples of 50-μm diameter fiber.

experimental conditions, namely the laser source and the distance between MSD and fiber, are left unchanged for test among different fiber samples. The variation in both inherent link bandwidth and subsequent SRE enhancement arise from the minute variations in fiber profile parameters and laser-to-fiber coupling.

Experimental results have suggested that 6x increase in link bandwidth can be achieved but at a prohibitively high penalty to responsivity. The embodiment of the SRE presented in this paper is deliberately chosen to provide a doubling of link bandwidth, specifically to match average performance achieved with restricted mode launch [1] but also to balance with induced penalty. On average, the embodied SRE achieves an average of 3.5-dB penalty among the tested fiber sample.

B. Bit Error Rate

In addition to measured temporal response, bit error rate (BER) is measured by transmitting a pseudo-random data bit stream in the fiber link. A photoreceiver includes the fabricated MSD, a 10-GHz transimpedance amplifier (TIA) provided by TriQuint Semiconductor, a 1-GHz noise filter, and a 10-GHz, 55-dB gain, limiting amplifier. The data rate at which the link is tested is 1.25 Gbps, which is not only the same as the clock rate of the Gigabit Ethernet but also approximately twice the rate sustainable by the fiber sample.

An eye-diagram and BER curve of received signal through the MMF link, with and without spatially resolved equalization, are presented in Fig. 5 and Fig. 6 respectively. The very high BER floor (10^{-2}) of the conventional MMF link is commensurate with the poor eye opening due to dispersion induced intersymbol interference. While with SRE, considerable improvement in the BER floor ($<10^{-9}$) is attained. A non-optimized PD response and the choice of a 10-GHz TIA (as opposed to a 1.25-GHz TIA), imposes an 8-dB power penalty to the receiver sensitivity but should have little effect on the SRE enhancement itself. With the necessary optimiza-

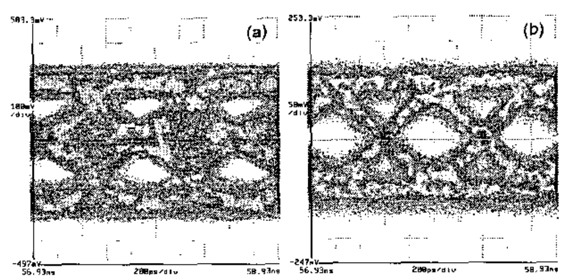

Fig. 5. Eye-diagram of received signal over 1.1-km, 50-μm MMF link driven by 1550-nm Fabry-Perot laser, externally modulated at 1.25 Gbps. (a) Standard MMF link. (b) SRE enhanced MMF link

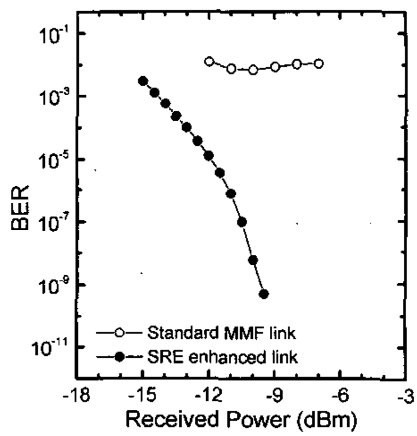

Fig. 6. Bit error rate measurement of received signal over 1.1-km, 50-μm MMF link driven by 1550-nm Fabry-Perot laser, externally modulated at 1.25 Gbps.

tion, the SRE receiver sensitivity better than -17 dBm should be achievable.

It should be noted that in general, a MMF link is susceptible to modal noise, which arises from potentially coherent interactions among the different modes at the detector [6]. The following three conditions must be met for modal noise to exist: coherent interaction among modes, fluctuation in phase velocity among the modes, and a spatial filtering of the output optical spot. Since SRE, by design, "spatially filters" the optical signal and unavoidable environmental drifts will readily produce fluctuation in phase velocity, it is critical to minimize coherent interaction among modes. This can be achieved by using a source with a low coherence time, smaller than the modal dispersion. For this reason, large-area multimode VCSEL well suited for minimizing modal noise [7]. Unfortunately, the unavailability of such laser at 1550-nm requires an alternative laser. An externally modulated Fabry-Perot (FP) laser with mode-scrambling is used to emulate the type of emission of VCSELs. The numerous lasing modes of the FP laser, along with the resulting polarization scrambling of both the fiber and laser modes serves to minimize the potential for modal noise at the output of the MMF with a net modal dispersion larger than 1 ns.

III. Conclusion

We demonstrate equalization of MMF link response by the use of a concentric, two-segment photodetector. The embodiment of the spatially resolved equalization presented is a subtraction of the PD signals that, in effect, filters out the contribution of several fiber modes, thereby reducing the effect modal dispersion in the fiber. Using various samples of fiber of common communication grade MMF, we demonstrated robust equalization without *a priori* knowledge of the exact fiber response. We show, through measured impulse response, that SRE can double the channel bandwidth. On the other hand, the filtering of fiber modes also results in average of 3.5-dB loss, however, most MMF link lengths are limited by dispersion not power. We also demonstrate a significant improvement in the BER floor by using SRE of a dispersion-limited MMF link.

Spatially resolved equalization can not only be independent of the precise channel response, eliminating the need for time consuming "training" of the system as with a conventional tap-delay-line equalizer, but SRE also maintains compatible with low-cost VCSEL, thereby maintaining all the advantages of multimode fiber with no significant increase in complexity as compared to a conventional MMF link.

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