10×10 Gb/s DWDM Transmission Through 2.2-km Multimode Fiber Using Adaptive Optics

Rahul A. Panicker, Jeffrey P. Wilde, Joseph M. Kahn, David F. Welch, and Ilya Lyubomirsky

***Abstract*—Transmitter-based adaptive optics and receiver-based single-mode filtering are combined to compensate modal dispersion in multimode fiber (MMF). A liquid-crystal spatial light modulator controls the launched field pattern for ten 10-Gb/s nonreturn-to-zero channels, wavelength-division multiplexed on a 200-GHz grid in the C-band. Error-free transmission through 2.2 km of 50-μm graded-index MMF is achieved for launch offsets up to 10 μm and for worst-case launched polarization. A ten-channel transceiver based on parallel integration of electronics and photonics is employed.**

***Index Terms*—Adaptive optics, modal dispersion, multimode fibers (MMFs), optical fiber dispersion, wavelength-division multiplexing (WDM).**

I. Introduction

MULTIMODE fiber (MMF) is widely used in short-reach systems such as local or storage networks, but modal dispersion limits reach at high bit rates. Methods used to mitigate modal dispersion include: wavelength-division multiplexing (WDM) of several lower bit-rate channels [1], single-mode launch with single-mode filtering at the receiver [2], [3], and adaptive optics at the transmitter [4]. Here, transmitter-based adaptive optics, receiver-based single-mode filtering, and WDM are combined to enable 100-Gb/s transmission over 2.2 km of MMF.

II. Experimental System

The experimental system is shown in Fig. 1. Data-bearing channels are generated and received by a 10×10 Gb/s dense WDM (DWDM) transceiver incorporating multichannel electronic and photonic integrated circuits (ICs), as described in [5]. On the transmit side, an electronic IC uses ten 10-Gb/s $2^{31} - 1$ pseudorandom bit sequence generators and forward-error-correction (FEC) encoders to generate ten 11.1-Gb/s bit streams. A transmit photonic IC includes ten distributed feedback lasers, electroabsorption modulators and variable optical attenuators, and an arrayed-waveguide grating (AWG) for wavelength multiplexing. An additional attenuator controls the total multiplexed launched power. Channels 1–10 are 11.1-Gb/s nonreturn-to-zero (NRZ) signals on a 200-GHz ITU grid on the long-wavelength side of C-band: 191.90–193.70 THz (1562.27–1547.75 nm). On the receive side, a photonic IC, integrating an AWG and p-i-n photodiode array, wavelength-demultiplexes and detects the ten 11.1-Gb/s NRZ signals. A receive electronic IC includes ten transimpedance amplifiers, clock/data recovery circuits, and FEC decoders. Each decoder monitors bit-error ratios (BERs) at its input and output and has threshold input BER $\sim 10^{-3}$, below which the output BER is zero. The FEC code provides $>$6-dB coding gain.

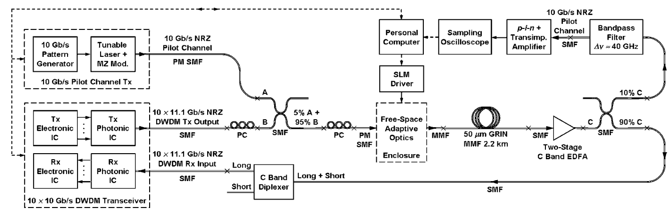

Fig. 1. Experimental setup. PC: polarization controller.

Two separate approaches for controlling the adaptive optics have been used. In the first approach, a pilot-channel transmitter, tunable on a 50-GHz ITU grid, encodes a periodic 10-Gb/s NRZ training sequence. The received pilot channel waveform is used to form an objective function for adaptation. This approach is referred to as "pilot channel adaptation." In the second approach, the pilot channel is omitted, and the FEC decoder input BERs are used to form an objective function for adaptation, a method referred to as "BER-based adaptation."

The ten 11.1-Gb/s data-bearing channels and optional 10-Gb/s pilot channel are copolarized, combined using a 95–5 coupler, and passed through a polarization-maintaining (PM) single-mode fiber (SMF) into the free-space adaptive optics system shown in Fig. 2. The system is described in detail in [4]. As shown in the inset of Fig. 2, the reflective nematic liquid crystal spatial light modulator (SLM) lies in the spatial Fourier plane of the input face of the MMF. The SLM is illuminated by the LP_{01} mode from the PM SMF, which has a numerical aperture (NA) of 0.11. The SLM is used to separately modulate the phases on each of 60 blocks covering 95% of the energy of the incident LP_{01} mode. While the SLM permits quasi-continuous phase adjustment, in order to minimize adaptation complexity, the phase over each block is uniform and restricted to take on one of four values from $\{0, \pi/2, \pi, 3\pi/2\}$. The SLM switching time ranges from 50 to 170 ms (10%–90%), depending on initial and final phase values. The beam reflected from the SLM is focused into the MMF, which has an NA of 0.19. The SLM enables adaptive control of the launched field pattern to minimize modal dispersion, while maximizing coupling from the MMF into an SMF at its output. Half- and quarter-wave plates control the state of polarization (SOP) of light launched into the MMF; as they are multiorder waveplates, the SOP is

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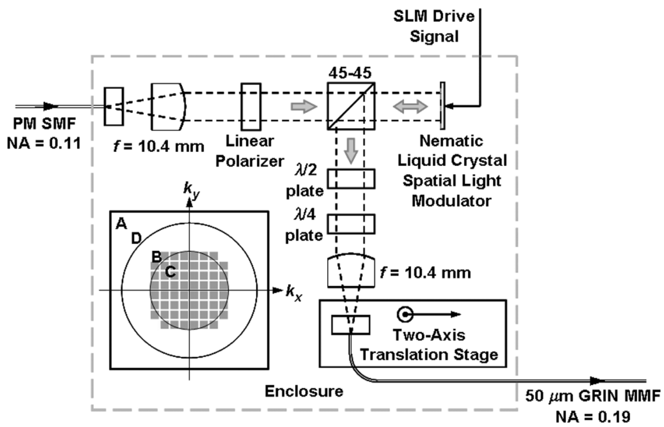

Fig. 2. Free-space adaptive optics subsystem. Inset: SLM in the Fourier plane of the input face of the MMF. A) boundary of SLM active region. B) Block structure of SLM pattern. C) Circle enclosing 95% of power of beam incident on SLM, corresponding to an NA of 0.11 at the MMF input. D) Circle corresponding to the MMF NA of 0.19.

not necessarily identical for all ten data-bearing channels. The input end of the MMF is placed on a two axis translation stage, enabling adjustment of the launch point relative to the center axis. The free-space system shown in Fig. 2 has an overall fiber-to-fiber loss of about 8.5 dB.

The transmission MMF is spooled, plastic-jacketed, 50-μm graded-index silica MMF (Corning InfiniCor eSX+), which is optimized for vertical-cavity surface-emitting laser transmission at 850 nm, and has not been optimized for transmission in the C-band. A 2.2-km length has a loss of 0.6 dB in the C-band.

The MMF output is butt-coupled to a standard SMF, providing spatial mode filtering. After the SLM is adapted, the MMF-to-SMF coupling typically produces a loss of about 2.3 dB. Once in the SMF, received signals are amplified by a two-stage erbium-doped fiber amplifier (EDFA) providing about 37.5-dB gain, flat over the C-band, and having a noise figure of about 4.6 dB. Ninety percent of the EDFA output is passed through a diplexer, and the long-wavelength side of the C-band is fed into the 10×10 Gb/s DWDM transceiver to decode the data-bearing channels. In pilot channel adaptation, 10% of the EDFA output is passed through a 40-GHz optical bandpass filter to select the pilot channel. The 10-Gb/s pilot channel is then detected, and the periodic waveform is sampled at an effective rate of eight samples per bit interval.

Recall that the SLM reflectance can be controlled over 60 blocks taking on quaternary phase values from $\{0, \pi/2, \pi, 3\pi/2\}$. Adaptation of the SLM uses an objective function to quantify the quality of the received signal. In an iteration of the adaptive algorithm, the 60 blocks are adapted one-by-one, proceeding outward from the center in concentric rings. At each block, the objective function is estimated for each of the four phase values, and the phase leading to the best value of the objective function is retained. Whereas [4] used a multimode receiver and required up to three adaptation cycles, here, a single-mode receiver is used, and only one cycle (60 blocks, four phases) is required.

In pilot channel adaptation, the pilot channel is tuned between data-bearing Channels 5 and 6, and transmits a periodic sequence of 64 “0” and 64 “1” bits. The received waveform is sampled, and the “abruptness” of the system step response is quantified as the difference between the largest positive and negative excursions of the received waveform over any two bit intervals separated by 64 bits, as in [4]. The SLM is adapted to maximize the “abruptness” of the system step response, thereby maximizing the peak of the system impulse response. An estimation of the objective function requires about 900 ms, limited mainly by sparse waveform sampling and latency over the general purpose interface bus, as in [4]. Adaptation of the entire SLM (60 blocks, four phases) requires about 4 min.

In BER-based adaptation, the pilot channel is omitted. The BERs of the ten data-bearing channels are measured at the FEC decoder inputs, and the SLM is adapted to minimize the sum of these BERs. An estimation of the objective function requires about 20 s, limited mainly by latency over the serial interface (the 10×10 Gb/s transceiver also incorporates a much faster Ethernet interface, but this was not used here). Adaptation of the entire SLM (60 blocks, four phases) requires about 20 min.

III. System Performance

Adaptation using each of the two methods has been tested in several runs.

In each run, the launch point is first adjusted to the center axis of the MMF. With center launch, in all test runs: 1) system performance is substantially insensitive to launched SOP; 2) the optical signal-to-noise ratio (OSNR, measured in a 0.1-nm bandwidth in two polarizations) ranges from 18.4 to 21.5 dB for all ten data-bearing channels; and 3) the OSNR margin with respect to the FEC threshold (quantified by BER measurements) ranges from 6.2 to 9.8 dB for all ten data-bearing channels.

In each run, in order to introduce severe impairment, the launch point is offset 10 μm from the MMF center axis. System performance then becomes sensitive to launched SOP, and the SOP is adjusted to yield approximately the worst performance in the worst of the ten data-bearing channels. With the 10-μm offset and bad SOP, some of the channels are subject to high attenuation and/or significant modal dispersion. Optical spectra and BER curves are measured prior to adaptation, and again after adaptation. Adaptation using each of the two methods consistently yields error-free performance in all ten channels.

Data are presented here from the worst run of BER-based adaptation. Fig. 3 shows optical spectra of the ten data-bearing channels, measured at the 10% output port of the 90–10 coupler. Fig. 4 shows the FEC decoder input BERs of the ten channels versus the transmitter attenuator setting; SLM patterns are also shown. Before adaptation [Figs. 3(a) and 4(a)], the OSNRs range from 9.8 to 17.4 dB, and five channels are unable to reach the FEC decoder threshold. After adaptation [Figs. 3(b) and 4(b)], the OSNRs range from 16.2 to 18.2 dB, and the OSNR margins with respect to the FEC threshold range from 3.4 to 6.4 dB.

IV. Discussion

Previous work using adaptive optics [4] employed a multimode receiver, resulting in a linear relationship between input and output intensity waveforms. In the current system using a single-mode receiver, that relationship is nonlinear. It appears that the system adapts to launch a field pattern exciting one or more principal mode(s) [6] that have nearly equal delays and that couple strongly to the fundamental LP_{01} mode in the single-mode receiver. In these silica MMFs with weak mode

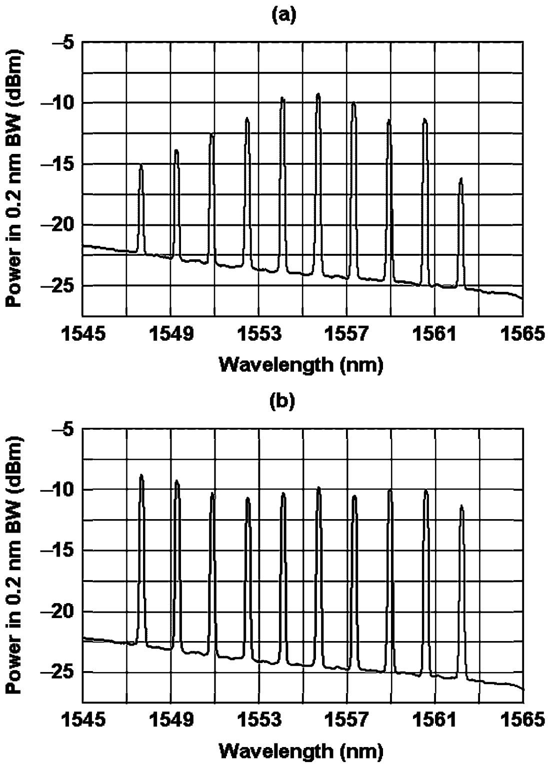

Fig. 3. Optical spectra of the ten data-bearing channels, with 10-μm offset launch and bad SOP. (a) Before adaptation. (b) After BER-based adaptation.

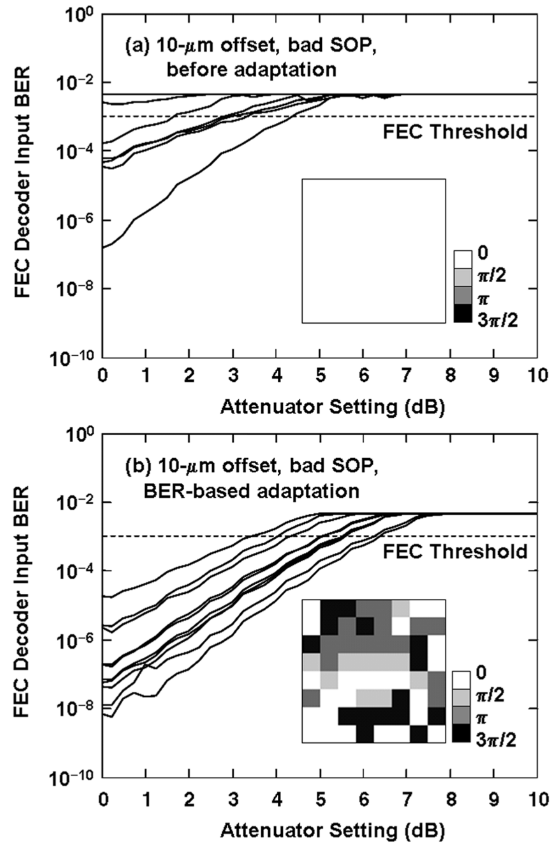

Fig. 4. BERs of the ten data-bearing channels at the FEC decoder inputs, as a function of the transmitter optical attenuator setting, with 10-μm offset launch and bad SOP. Insets show the SLM patterns. (a) Before adaptation. (b) After BER-based adaptation.

coupling, it is believed that these principal mode(s) are linear combinations of mainly low-order modes of an ideal MMF.

The experimental system, once adapted, is limited mainly by EDFA noise, not by modal dispersion. The OSNR margin could be increased by: 1) decreasing the loss of the adaptive optics subsystem; 2) increasing the launched power per channel; or 3) moving the EDFA to the input side of the adaptive optics subsystem. Option 3 would require a PM EDFA or a polarization-insensitive SLM. In the experimental system, adaptation time is limited primarily by estimation of the objective function (0.9 or 20 s) and secondarily by switching of the SLM (<200 ms). Using optimized hardware, it is believed that objective function estimation could be performed in 25 μs, and SLM switching in 100 μs, so that overall adaptation (60 blocks, four phases) could be performed in about 30 ms.

In the experimental system, the launched field distribution is stable, but the MMF exhibits time-varying mode coupling. A single-mode receiver is employed, so the potential for modal noise exists. The only observed manifestation is a drift of received power and/or modal dispersion on a time scale of seconds to minutes. The drift is negligible for center launch. With 10-μm offset launch, the drift is pronounced before adaptation, but after adaptation, the system is stable for at least several minutes. In a practical system, modal noise would potentially be caused by MMF perturbations on a time scale shorter than the system adaptation time (e.g., about 30 ms in an optimized system). Modal noise might be minimized by eliminating the EDFA and using a multimode demultiplexer [7] and multimode receivers.

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