Fig. 2. Block diagram of 622 Mb/s GPON experimental setup with the BMRx (OSC: oscilloscope).

bandwidth to filter out noise while keeping inter-symbol interference to a minimum [7].

The bursty upstream PON traffic as in [6], is generated with adjustable phase $(-2\pi \leq \Delta\varphi \leq +2\pi$ rads$)$ from programmable ports of a pattern generator (PG), which are then concatenated via a power combiner (PC) and used to drive the EOM. These packets are formed from: 16 guard bits, 0 to 28 (l) preamble bits, 20 delimiter bits, $2^{15} - 1$ payload bits, and 48 comma bits. The guard, preamble, and delimiter bits correspond to the physical-layer upstream burst-mode overhead of 8 bytes at 622 Mb/s as specified by the G.984.2 standard [4]. The guard bits provide distance between two consecutive packets to avoid collisions. The preamble field is used to perform amplitude and phase recovery. The delimiter is a unique pattern indicating the start of the packet to perform

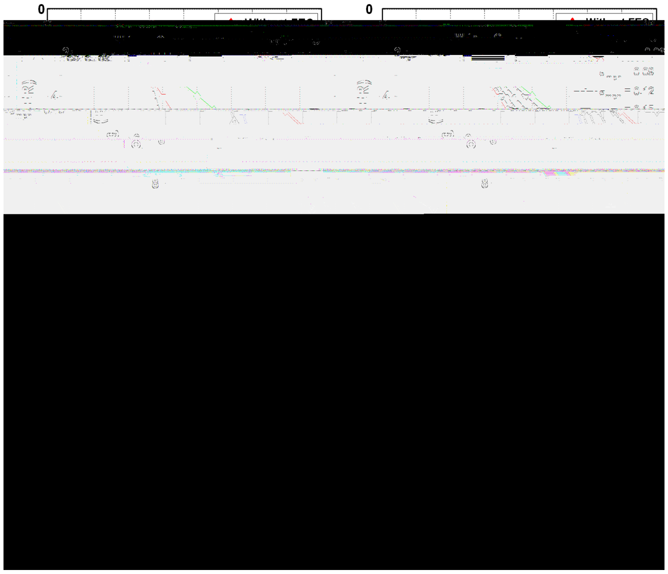

Fig. 3. (a) BER performance. (b) Effect of MPN. (c) Effective coding gain and MPN penalty. (d) Theoretical effective coding gain with worst-case MPN.

overestimated for BER $< 10^{-4}$. This is attributed to the fact that as the received power is increased, the presence of random errors is attenuated relative to the presence of deterministic errors. This is more likely due to the memory added in the channel through intensity noise, deterministic jitter, CDR, and other components, making the errors statistically dependent in a GPON uplink. An interleaver may be used to arrange the data in a non-contiguous way such that the codeword bits are interleaved before being transmitted. Thus, in the presence of deterministic jitter, only a correctable number of bits in each codeword will be affected. This however, increases latency.

MPN is a phenomenon occurring because of an anti-correlation among pairs of longitudinal modes and has been studied extensively in [9]. That is, even though the total intensity of the modes remains relatively constant, various longitudinal modes fluctuate in such a way that individual modes exhibit large intensity fluctuations [3]. This leads to the different modes becoming unsynchronized because of group-velocity dispersion. Thus, the signal-to-noise ratio (SNR) at the decision circuit becomes worse than that expected in the absence of MPN. Consequently, a power penalty must be paid to improve the SNR to the same value that is necessary to achieve the required BER. The power penalty caused by MPN existing in 1330-nm lightwave systems has been analyzed in [10].

Suppose the time average spectrum of the laser source is assumed to be Gaussian and the half spectrum width is σ_λ, then the mean square variance of MPN σ_{mpn}, is determined by [10]

$$\sigma_{mpn} = \frac{k}{\sqrt{2}} \left[1 - e^{-(\pi B D L \sigma_\lambda)^2} \right] \quad (4)$$

where k is the mode partition coefficient, B is the bit rate, D is the fiber delay dispersion per unit lengh per unit wavelength, and L is the fiber length. If MPN did not exist in the system, the signal power S_o which is required to achieve a given BER would be $1/Q^2 = (\sigma_o/S_o)^2$ where σ_o is the total receiver power and Q is determined by the BER $p_e = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right)$. The required signal power S_m to achieve the same BER when MPN is added to the receiver noise becomes [11]

$$\frac{1}{Q^2} = \left(\frac{\sigma_o}{S_m}\right)^2 + \sigma_{mpn}^2 \quad (5)$$

and the resulting power penalty caused by MPN δ_{mpn}, is then [9]

$$\delta_{mpn} = 10 \log \left(\frac{S_m}{S_o}\right) = -5 \log \left(1 - Q^2 \sigma_{mpn}^2\right) \quad (6)$$

The coding gain G (when $\sigma_{mpn} = 0$) obtained by employing FEC will then also have to compensate for the power penalty δ_{mpn}, giving an MPN power penalty after FEC δ_{mpn}^{FEC}. Consequently, the effective coding gain G_{eff} (when $\sigma_{mpn} = 0$) of the system will decrease with 974T3obi-542.a9m134.0F7

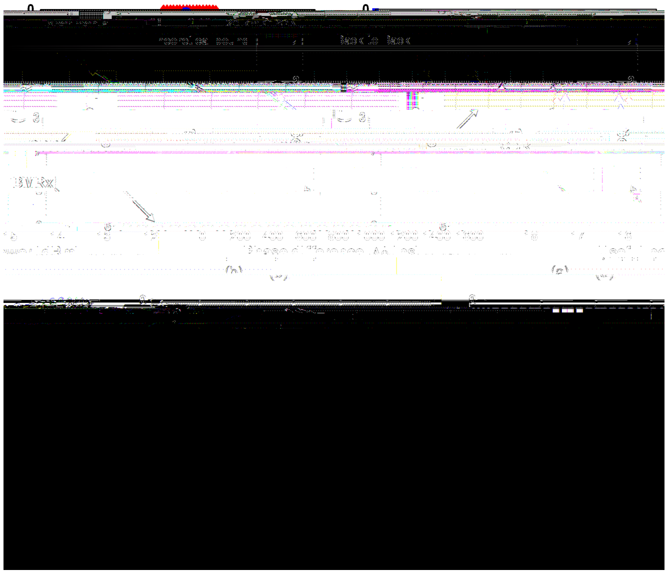

Fig. 4. (a) PLR performance. (b) Comparison of simulated and measured PLR. (b) PLR vs. BER performance with a pattern correlator having different error resistance values in a delimiter. (d) Effect of MPN.

is increased, there is an improvement in the PLR. After 32 preamble bits, we observed error-free operation $(\text{PLR} < 10^{-6})$ for any phase step. However, the use of the preamble reduces the effective throughput and increases delay. Also, a 32-bit preamble does not satisfy the 28-bit requirement specified in the G.984.2 [4]. With the introduction of a 20-km of fiber uplink, it can be observed from Fig. 4(a), that there is a degradation in the PLR performance. However, by switching on the burst-mode functionality of the receiver with the CPA, we observe error-free operation in both configurations for any phase step $|\Delta\varphi| \leq 2\pi$ rads with *no* preamble bits, allowing for instantaneous phase acquisition[2]. This is well below the 28-bit GPON specification.

A delimiter of a packet that cannot be detected correctly will lead to the packet being lost. The error resistance of the delimiter depends not only on its length, but also on the exact implementation of the pattern correlator. If the pattern correlator has an error resistance of z bits in a d-bit delimiter, then the PLR at a given BER of p_e can be estimated as

$$\text{PLR} \leq \sum_{j=z+1}^{d} d \; jdpje($$