400-Gb/s Transmission Over 10-km SSMF Using Discrete Multitone and 1.3-μm EMLs

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***Abstract*— We experimentally demonstrated 400-Gb/s transmission over 10-km standard single-mode using discrete multi-tone (DMT) and four 1.3-μm local-area-network wavelength-division-multiplexed externally modulated lasers. A reasonably good system margin has been obtained. We have also investigated the fundamental limitations of using semiconductor optical amplifiers for DMT-based systems.**

***Index Terms*— 400G, DMT, LAN-WDM, optical modulation, semiconductor optical amplifiers.**

I. Introduction

DISCRETE-MULTITONE (DMT) is a modulation technique which provides a configurable frequency-dependent bit-loading in accordance to the available granular bandwidth of a transmission line, and consequently a very high spectral efficiency. It has been widely used in copper wire-based digital subscriber loop (DSL) systems for many years, and has been proposed as a method to transport multiple tens of gigabit/sec data over single-mode [1] and multi-mode fibers [2]. Most recently, 100Gb/s [3] and 400Gb/s [4] transmissions have been demonstrated to be feasible over a distance ≥10km. In [3] and [4], however, the link power budget was not sufficient to meet the 10km SSMF requirement (i.e., 6.3dB) set by IEEE802.3ba [5]. Therefore, in this letter, we experimentally demonstrate a 400Gb/s transmission over 10km SSMF with a sufficient link power budget using four LAN-WDM EMLs. In addition, we also carried out an experiment to show the fundamental limitations of using a semiconductor optical amplifier (SOA) to extend the transmission distance or increase the link power budget.

II. Experimental Setup

The experimental setup is shown in Figure 1. The generated DMT signal from off-line processing was downloaded into a 4-channel digital-to-analog (DAC) and then amplfiied by an array of linear driver amplifiers. Each of the four driver outputs drove separate 1.3μm EMLs which were separated by 3.5∼5.5nm. Due to the variance among the EML optical power-bias voltage curves, each EML was driven with their own optimized bias voltages and voltage swing. In addition to the driving conditions, the wavelengths were temperature adjusted to equalize the output power to within 1 dB- this is the reason why the wavelength at 1309nm was moved to 1308nm by lowering its operating temperature in order to increase its ouput power.

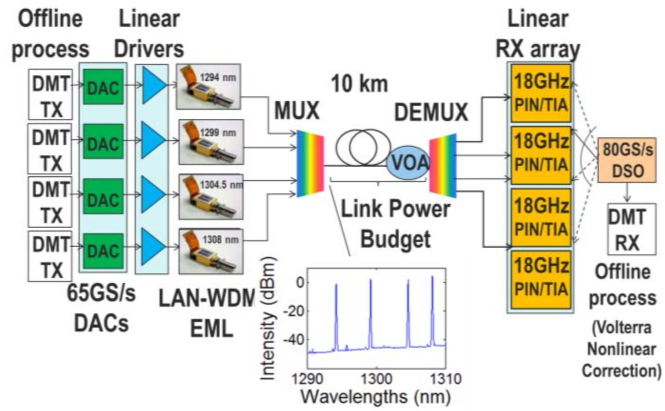

Fig. 1. Experimental Setup.

The four wavelengths were multiplexed by a LAN-WDM multiplexer and transmitted over 10km SSMF. To simulate additional link loss, we included a variable optical attenuator (VOA) after the fiber, as shown in Fig. 1. The wavelength channels were subsequently demultiplexed by a matched demultiplexer and separately measured using a linear optical receiver, which is composed of a high-speed photodiode and a linear transimpedance amplifier (TIA). The gain of the TIA was adjusted to balance the receiver linearity and noise performance. The received signal was then sampled at 80GSa/s on a real-time oscilloscope and the data was extracted for offline digital signal processing (DSP). The key parameters of the experiment are listed in Table I.

The DMT signals were encoded using Matlab with the following parameters: FFT size=512, cyclic prefix=8 (1.5% overhead), number of subcarriers=176 (out of a possible 256 subcarriers were used- due to the ∼21GHz usable bandwidth of the optical transceivers). Also, for every data frame, there are 250 data symbols, 10 training symbols, and 1 sync symbol. The total data rate is 106Gb/s, and the net data rate is 100.5Gb/s.

We have also applied a Volterra non-linear filter [6] at receiver-side DSP to correct the nonlinear distortions caused by each EML and optical receiver pair. The non-linear filter

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TABLE I
PARAMETERS FOR THE EXPERIMENT

	Parameter	Value
1.	3-dB bandwidth of DAC evaluation board plus linear driver amp	13 GHz
2.	DAC sampling rate	63 GSa/sec
3.	ADC 3-dB bandwidth	25 GHz
4.	ADC sampling rate	80 GSa/sec
5.	1.3μm EML 3-dB bandwidth	21 GHz
6.	Linear receiver 3-dB bandwidth	22 GHz
7.	Receiver noise spectral density	30 pA/√Hz

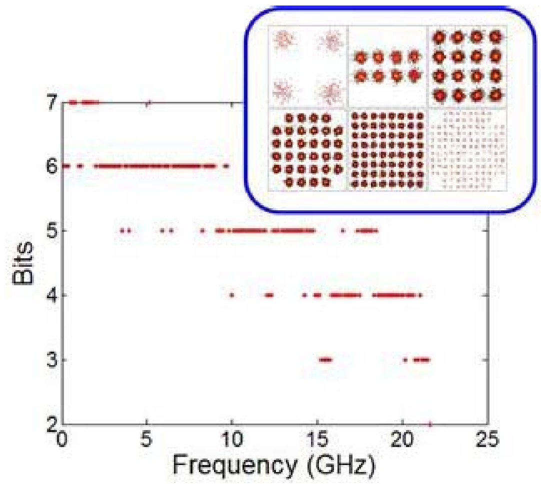

Fig. 2. Bit loading generated from the SNR spectral response. The measured constellations are shown in the inset. $\lambda = 1294$ nm.

that was used consisted of 1st, 2nd and 3rd order coefficients with a memory depth of 4.

III. MEASURED RESULTS

Fig.2 shows the measured bit loading as a function of frequency, and the received constellation diagrams, for a back-to-back 1294nm optical link and at a bit-error-rate (BER) of 1.6e-4. As shown in the figure, most subcarriers within the 13GHz analog bandwidth of the DAC evaluation board can offer a high spectral efficiency of 5∼7bits/sec/Hz. This is the main reason why DMT can use an optical transmitter and receiver with a bandwidth just around 20GHz to carry a 100Gb/s data stream.

To measure the link power budget (defined in Fig. 1), which excludes the loss of WDM mux and demux), the bit loaded signals were transmitted over 10km of SSMF as the attenuation was varied. Apart from the VOA, the measured link budget includes insertion loss from optical connectors, 10km SSMF spool, and the loss from an inline optical power monitor. As shown in Fig. 3, a $\geq$ 7.9dB link budget for a BER $\leq 10^{-3}$ was obtained. This is 1.6dB more than what is required by IEEE802.3ba [5] for a 10km SSMF link. This superior performance is achieved thanks to (a) a consistently high output power of $\geq$ 5.0dBm from all EMLs, (b) a consistently high receiver sensitivity of ≤ -5.0dBm from all receivers; and (c) a consistently low insertion loss of $\leq$ 2.2dB from all MUX and DEMUX ports. Table II shows the EML output power, receiver sensitivity, and link power budget for each λ.

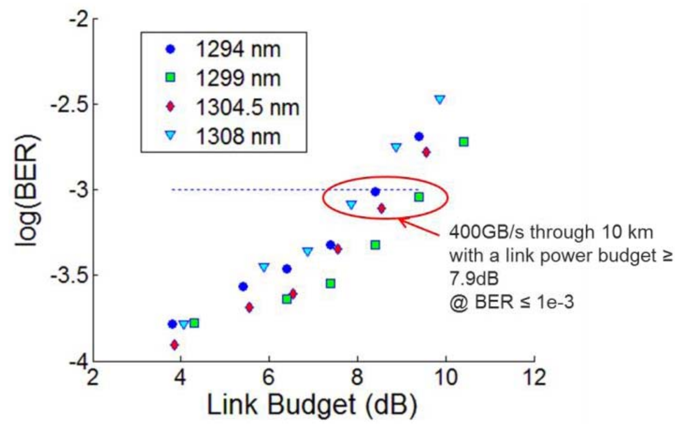

Fig. 3. BER vs. link power budget for all four wavelengths.

TABLE II
EML OUTPUT POWER, RX SENSITIVITY, AND LINK POWER BUDGET

Wavelength (nm)	TX Power (dBm)	WDM Mux Loss (dB)	Link Budget (dB)	WDM Demux loss (dB)	Rx Power (dBm)
1294	5.4	1.45	8.41	1.04	-5.5
1299	5.5	1.66	9.11	0.83	-6.1
1304.5	5.0	1.66	8.73	1.31	-6.7
1308	6.1	2.22	7.87	1.01	-5.0

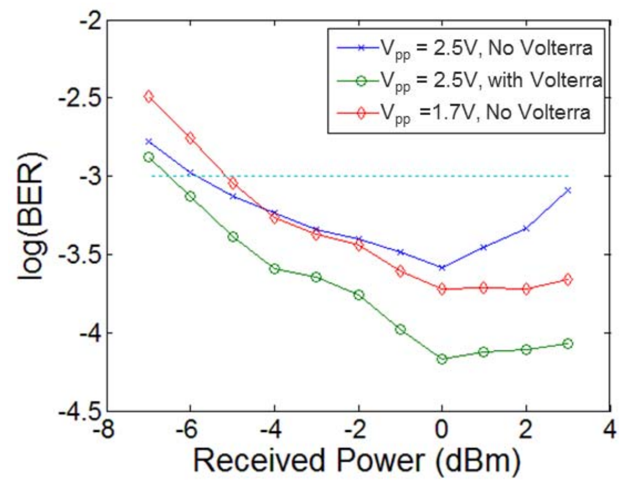

Fig. 4. BER vs. received optical power under different driving signal amplitudes, and with or without Volterra nonlinear compensation.

The measured results of a typical receiver sensitivity performance and the effect of Volterra nonlinear correction are shown in Fig. 4. The red curve represents the achievable BER obtained without any nonlinear correction. A driving signal amplitude of 1.7V_{pp} was applied to an EML to maintain a near linear signal response. In this case, a BER of 1e-3 was achieved when the received optical power was beyond -5dBm. The receiver sensitivity was improved to -6.5dBm by increasing the voltage swing to 2.5V_{pp} and correcting for the nonlinearities with Volterra series post-processing, as shown by the green curve. For comparison purposes, the uncorrected 2.5V_{pp} signal is shown by the blue curve. It can be

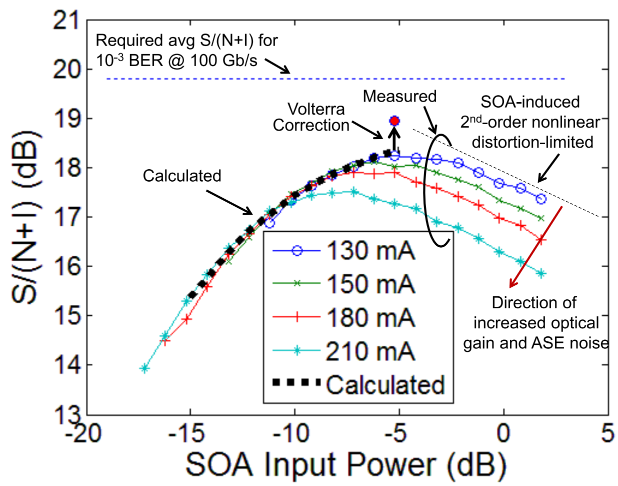

Fig. 5. S/(N+I) vs. SOA input power. Each measured curve shows the response at different SOA drive current. The calculated data points are based on [7].

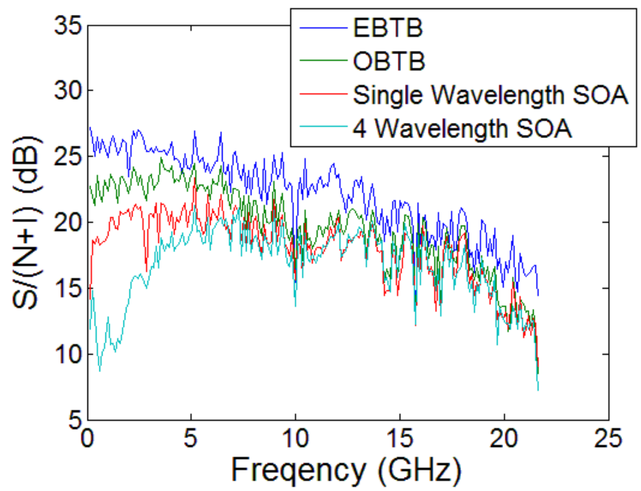

Fig. 6. Frequency-dependent S/(N+I) distribution. EBTB: Electrical Back-to-Back; OBTB: Optical Back-to-Back. Input signal power to the SOA is given by subtracting an EML output power by the combined optical loss of MUX and link budget shown in Table II.

seen that, due to the higher modulating voltage swing-induced TIA nonlinearity, $2.5V_{pp}$ starts to get a worse BER than that of $1.7V_{pp}$ beyond a received power of 0dBm.

As shown in Fig. 4, even without Volterra nonlinear compensation, a good receiver dynamic range can be obtained whether the driving voltage at the EML was 1.7 or $2.5V_{pp}$. This is because the TIA has an excellent linearity performance-it can maintain a 2% total harmonic distortion (THD) even when its differential input current is as high as $2.5mA_{pp}$.

Next, we would like to investigate the possibility of using an SOA to further increase the link power budget, or extend the transmission distance. The investigation was carried out by placing an SOA after the 10km SSMF and the VOA in Fig. 1. We have spliced optical isolators at both the input and output of the SOA pigtails to avoid significant intensity noise increase due to amplified multipath interference. In this experiment, a VOA was used to adjust the SOA input power and find the optimum operation point. The resulting signal to (noise + interference) ratio or S/(N+I), averaged over 176 probing 16-QAM subcarriers, is plotted in Fig. 5 for the 1304.5nm wavelength EML. The interference comes from subcarrier-to-subcarrier intermixing (or SSII), which in turn is caused by the nonlinearities of EML, TIA, and SOA. As shown in Fig. 5, an average S/(N+I) of 19.8dB serves as a first-order indicator that the system can pass a capacity of >100Gb/s at a BER of 1e-3, which is a convenient indicator before we carry out the actually bit-loading and bit error count. At a low SOA input power, the S/(N+I) is limited by system intensity noise, SSII, and signal-spontaneous beat-noise. A calculated result based on RIN=-135.5dB/Hz (which includes SSII), SOA noise figure=7.3dB, optical modulation index=4% (optical modulation index per subcarrier is defined as the ratio of half the optical peak-to-peak intensity variation per subcarrier to the average optical power, and is averaged over all subcarriers), bandwidth per subcarrier=245MHz, and thermal noise spectral noise density=30pA/$\sqrt{\text{Hz}}$ is shown in Fig. 5. At a high SOA input power when the SOA was run into saturation, the S/(N+I) is mainly limited by SOA-induced 2^{nd}-order SSII. This phenomenon can be confirmed by the S/(N+I) degradation in the low frequency range below ~7GHz, as shown in Fig. 6, which is caused by the 2^{nd}-order SSII that occur mainly at low- and high-end frequency ranges (the high-end frequency S/(N+I) degradation cannot be seen due to the already low S/(N+I) in that frequency range).

Our Volterra compensation can improve the optimum S/(N+I) by about 0.8dB at the optimum SOA input power, as shown in Fig. 5. Although a Volterra series with a larger memory depth at 2^{nd} order can further improve the S/(N+I) [8], the corresponding power consumption increase may not justify its use.

When all four wavelengths are transmitted through the 10km SSMF, the VOA, and the SOA, a further degradation of the peak SNR in Fig. 5 by 1.5~2dB due to cross gain modulation was observed. This degradation is shown in Fig. 6 by the light blue curve. The cross gain modulation penalty also manifests at low frequencies.

Fig. 6 also shows the S/(N+I) of the measured back-to-back electrical signal and of the back-to-back optical signal before it is transmitted through the fiber. The degradation caused by electrical to optical conversion is approximately constant across all frequencies, which is in contrast to low-frequency SNR degradation due to the SOA-induced nonlinear distortions.

Note that all SNR and BER measurements represent the optimum obtained value out of ten measurements of the same DMT signal. Using the parameters of our DMT signal outlined above, one DMT signal represents 44000 different data symbols with 250 symbols per carrier. In addition, SNR measurements are calculated using the error vector magnitude (EVM) that is obtained from the received constellations.

IV. Discussion

Although DMT's high spectral efficiency enables the use of optical transmitters and receivers with a bandwidth of only ~20GHz to transport 100Gb/s, practical implementation of DMT for 2 or 10km transmission at 1.3μm will depend on the power consumption of DMT ASIC in comparison to that of an ASIC for other modulation techniques. The effect of FFT size [9] and Volterra nonlinear compensation on the total power consumption should also be carefully studied.

Note also that even though a directly modulated laser (DML) can offer a higher optical power than that of an EML, the overall link power budget can be comfortably achieved by using the combination of an EML and a linear receiver with a high sensitivity.

V. Conclusion

We have experimentally demonstrated the first 400Gb/s 10km SSMF transmission link with a sufficient link power margin (1.6dB more than the 6.3dB required by [5]) by using four high-power ($\geq +5$dBm) LAN-WDM EMLs and high-sensitivity linear receivers (≤ -5dBm). The effect of Volterra nonlinearity compensation and the limitation of SOA for DMT systems at 1.3μm have also been studied.

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