10-Gb/s Transmission of 1.55-μm Directly Modulated Signal over 100 km of Negative Dispersion Fiber

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***Abstract*—In this letter, the largest transmission distance (100 km) ever reported for a commercially available 10-Gb/s 1.55-μm directly modulated signal over a single fiber link without using any dispersion compensation is demonstrated. The achieved dispersion-length product for a Q-factor greater than 9.4 dB (bit-error rate less than 10^{-15}) was about 750 ps/nm. The fiber that enabled such long transmission distance with high dispersion tolerance is a nonzero dispersion-shifted fiber that has negative dispersion in the entire usable bandwidth (1280–1620 nm) and is optimized for operation with directly modulated lasers. The excellent single-channel transmission performance that we achieved can be expected also from wavelength-division-multiplexed systems with channels across the erbium-doped fiber amplifier bands.**

***Index Terms*—Directly modulated lasers, fiber dispersion, optical communication systems.**

I. Introduction

COST-EFFECTIVE directly modulated distributed feedback lasers (DMLs) have attracted much attention recently for application in metropolitan area systems. The high output power of 1.55-μm DMLs can provide a power budget that allows for amplifier/regenerator spacing of 80–100 km. However, the frequency chirp characteristics of DMLs significantly limit the maximum achievable transmission distance over standard single-mode fibers (SSMFs) [1]. This is especially true for operation at high bit rates (10 Gb/s), where the chirp becomes more pronounced. We should point out that at 10 Gb/s the dispersion-limited distance of commercially available 1.55-μm DMLs is usually less than 10 km, while the dispersion tolerance (dispersion-length product) of an ideal chirp-free ASK signal with infinite extinction ratio (at 2-dB dispersion-induced eye-closure penalty) is less than 1100 ps/nm [2]. Therefore, 10-Gb/s DMLs were developed initially for the 1.3 μm wavelength band, where the dispersion of SSMF is very small. It is only recently that 10-Gb/s DMLs were developed for the 1.55-μm wavelength band for short reach applications. At this band, the use of a dispersion-shifted fiber (DSF) with a zero-dispersion wavelength around 1550 nm will result in long transmission distances but will not enable the application of wavelength-division-multiplexed (WDM) technology.

Electroabsorption modulator integrated distributed-feedback lasers (EA-DFBs) are another possible solution as 10-Gb/s 1.55-μm sources [3]. Commercially available 1.55-μm EA-DFBs are specified for a dispersion tolerance up to 1600 ps/nm ($\sim$ 90 km of SSMF). However, their output power is small ($\sim$ 5–10 dB lower than that of DMLs) and the use of optical amplification is needed for successful detection at long distances.

The absence of amplification in a system will result in reduced costs and complexity. For such unamplified systems, the DMLs is an attractive solution if the dispersion penalty is not significant. Previous studies have tried to increase the dispersion-limited distance of DMLs over standard fibers [4]. However, such solutions result in increased system costs and/or complexity. Therefore, an optical fiber that will increase the dispersion-limited distance to 80–100 km when using high-power 10-Gb/s 1.55-μm DMLs while enabling WDM technology is of significant importance. We believe that the use of a negative dispersion fiber that will take advantage of the "positive" transient chirp of DMLs (i.e., blue-shifted leading edge/red-shifted trailing edge) [1], [5], [6], will dramatically enhance the capabilities of 10-Gb/s directly modulated lasers. The use of negative dispersion fiber (e.g., MetroCor fiber)[1] has been demonstrated for successful transmission of 32 C-band directly modulated WDM signals operating at 2.5 Gb/s [5].

In this letter, we investigate the transmission performance of a commercially available 1.55-μm 10-Gb/s DML over a negative dispersion fiber for different bias and driving conditions. The negative dispersion fiber used in the experiments was Corning's MetroCor fiber, with a zero-dispersion wavelength beyond L-band and negative dispersion in the entire usable bandwidth (1280–1620 nm). For a Q-factor higher than 9.4 dB (bit-error rate less than 10^{-15}), a transmission distance of 100 km is achieved for a directly modulated signal with an extinction ratio of 5 dB without using any dispersion compensation while the fiber presented significant negative dispersion at the operating wavelength. The achieved dispersion-length product was as high as 750 ps/nm. We also demonstrate error-free transmission over 75 km without dispersion compensation and preamplification for a directly modulated signal with an extinction ratio of 8 dB. For the same conditions, the maximum distance achieved over SMF-28 fiber is about 10 km. The results of our single channel experiments can be extended to predict the behavior of a WDM system with channels across the erbium-doped fiber amplifier (EDFA) bands. Based on the high value of the achieved dispersion-length product of about 750 ps/nm and our previous experiments with 2.5-Gb/s signals [5], we believe that similar performance can be achieved for channels across the EDFA-bands.

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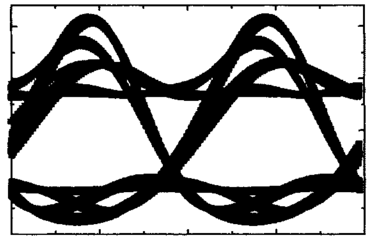
[1]MetroCor is a trademark of Corning, Inc.

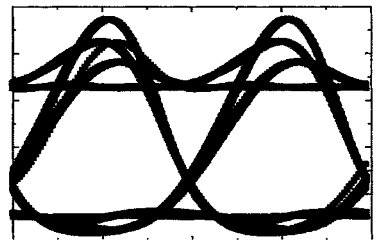
II. Results and Discussion

A 1.55-μm commercially available 10-Gb/s DML (NLK-1551-SSC) was used in our experiments. The laser wavelength was 1541.81 nm and its threshold current 15.3 mA. At a bias current of 50 mA, the output power was $\sim$6 dBm and the 3-dB modulation bandwidth $\sim$20 GHz. The power and chirp waveforms were measured for various driving conditions and it was found that the laser presented strong transient chirp. The DML was characterized using the experimental procedures described in [6] and the rate equation parameters associated with it were determined. The measured α-parameter value of about 2.7 should not be considered very small but rather typical. Simulations were then performed using the rate equations laser model [5] and the extracted parameters as well as the characteristics of MetroCor fiber. MetroCor fiber has "normal" dispersion (negative D) at the entire wavelength window that EDFAs work. Its average dispersion is about -3 ps/nm $\cdot$ km in the L-band and about -8 ps/nm $\cdot$ km in the C-band while its attenuation, effective area and dispersion slope is similar to other conventional nonzero dispersion shifted fibers. The launched power into the fiber was assumed to be 5.5 dBm. Using our simulation tool we calculated eye-diagrams of the received optical signal for various driving conditions of the DML and for various transmission lengths of either MetroCor or SMF-28 fibers. Some simulation results are presented in Fig. 1. As can be seen by the high quality of the received eye diagrams a transmission distance of about 100 km could be supported. A transmission experiment was then performed to validate the simulation predictions.

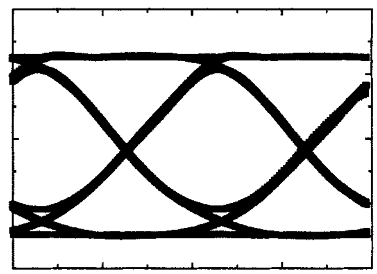
A $2^{31}-1$ pseudorandom bit sequence (PRBS) signal, provided by the signal generator of a bit-error-rate test-set (BERT), was used to drive the DML at 10 Gb/s. By varying the amplitude of this signal we could achieve different extinction ratios (ER) for the modulated optical signal. An electrical amplifier was used in the cases that the modulation voltage needed for high ER was larger than the maximum available voltage from the BERT. The use of the particular amplifier degraded the quality of the electrical driving signal and that consequently resulted in degradation of the performance of the transmitted optical signal. The 10-Gb/s optical signal produced by the DML was then transmitted over various lengths of either SMF-28 or MetroCor fiber. The launched power into the fiber was 5.5 dBm, to ensure large optical signal-to-noise ratio (OSNR) for the received signal. Since the signal wavelength is at the "normal" dispersion regime of MetroCor fiber, an increase of signal power beyond a certain value will cause performance degradation due to nonlinear effects (no performance improvement is expected for a moderate launch power level, as it is the case in the "anomalous" dispersion regime). For our single-channel experiment, the launched power level used did not cause any significant degradation in the transmission performance due to self-phase modulation. A typical optical preamplifier was used in some cases to provide the necessary power into the receiver. The power into the receiver (after the preamplifier) was kept always constant to about -7 dBm. No dispersion compensation was used at any point of the transmission link. The performance of the detected signal was determined by measuring the Q-factor (the Q-factor is expressed in dBs as: $Q_{\rm dB} = 10 \log Q_{\rm linear}$).



(a)



(b)



(c)

Fig. 1. Simulated eye-diagrams for transmission over: (a) 100 km of MetroCor fiber for an extinction ratio of 5 dB, (b) 75 km of MetroCor fiber for an extinction ratio of 8 dB, and (c) 10 km of SMF-28 fiber for an extinction ratio of 8 dB.

Two different driving conditions were used in our experiments. In the first case the laser bias current was 55 mA and the modulation voltage provided by the BERT was $2V_{\rm p-p}$. These conditions resulted in a dynamic extinction ratio of 5 dB. In the second case the bias current was 70 mA and using an amplified electrical driving signal we could achieve an ER of 8 dB. For the first bias and driving conditions, the measured peak-to-peak transient chirp was $\sim$19 GHz, while for the second set of conditions the peak-to-peak transient chirp was $\sim$39 GHz.

In a first set of experiments, the performance was measured using an optical preamplifier before the receiver. A transmission distance of 100 km over MetroCor fiber was achieved with a Q-factor of 9.4 dB (BER $< 10^{-15}$) for a directly modulated signal with an ER of 5 dB. That distance over MetroCor fiber corresponds to a dispersion-length product of about 750 ps/nm. We believe that this is the largest dispersion-length product ever achieved for 10-Gb/s directly modulated signals. With such high values of the dispersion-length product we are certain that very good transmission performance can be achieved for channels across the C- and L-EDFA bands. In the case of 8-dB ER a Q-factor of 9.3 dB was measured for a transmission distance of 75 km over MetroCor fiber.

Since the main advantage of DMLs relative to externally modulated sources is the high available output power, we

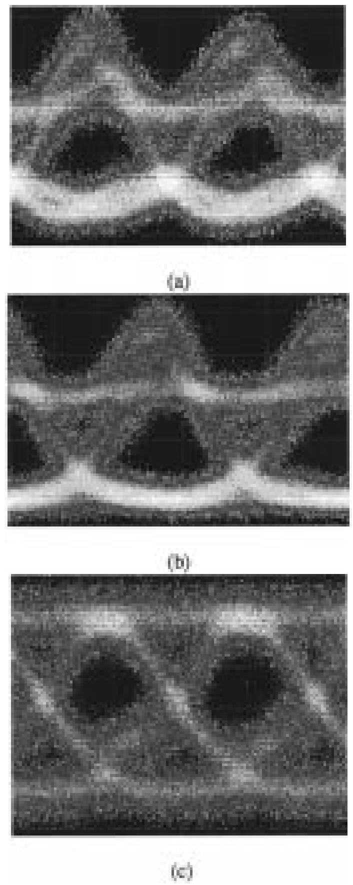


Fig. 2. Measured eye-diagrams for transmission over: (a) 100 km of MetroCor fiber for an extinction ratio of 5 dB, (b) 75 km of MetroCor fiber for an extinction ratio of 8 dB, and (c) 10 km of SMF-28 fiber for an extinction ratio of 8 dB.

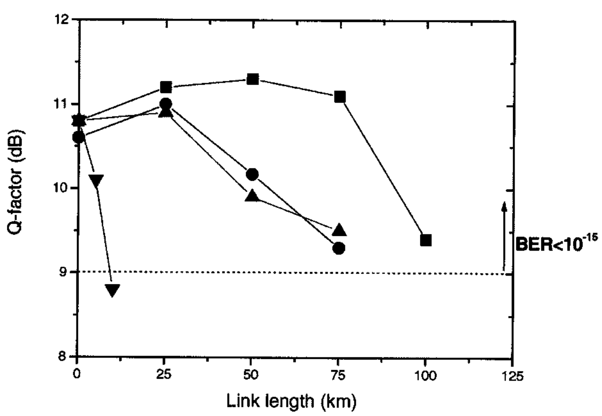


Fig. 3. Q-factor measurements of the received signal after transmission over various lengths of MetroCor and SMF-28 fibers. MetroCor fiber—$\mathrm{ER} = 5$ dB—with preamplifier (squares), MetroCor fiber—$\mathrm{ER} = 8$ dB—with preamplifier, (circles), MetroCor—$\mathrm{ER} = 8$ dB—without preamplifier (up triangles), SMF-28—$\mathrm{ER} = 8$ dB—without preamplifier (down triangles).

measured the transmission performance of the system without amplification at any point. In this second set of experiments, for a directly modulated signal with an ER of 8 dB, we achieved a Q-factor of 9.5 dB after a transmission distance of 75 km of MetroCor fiber. As expected, the Q-factor is similar to what was achieved without the optical preamplifier since the OSNR was in both cases very high (larger than 28 dB) and the receiver was thermal noise- and not OSNR-limited. For the same conditions we measured the performance over 10 km of SMF-28 fiber. A Q-factor of only 8.8 dB was measured.

In Fig. 2, we present the measured received eye-patterns for the cases of transmission over (a) 100 km of MetroCor fiber $(\mathrm{ER} = 5\ \mathrm{dB})$, (b) 75 km of MetroCor fiber $(\mathrm{ER} = 8\ \mathrm{dB})$ and (c) 10 km of SMF-28 fiber $(\mathrm{ER} = 8\ \mathrm{dB})$. The simulation predictions (shown in Fig. 1), obtained using the extracted parameters for the specific 10-Gb/s DML [6] and for the experimental conditions (same extinction ratios, same power, etc.) shows very good agreement with the experiment. The shapes of the calculated and measured eye-diagrams for the various conditions are very similar.

Fig. 3 summarizes the Q-factor measurements over different lengths of SMF-28 and MetroCor fibers for various driving conditions. We should note that in the cases of transmission over MetroCor fiber, a Q-factor improvement relative to the back-to-back values could be observed up to a certain transmission distance. The improvement in the Q-factor was up to 0.5 dB at a distance as long as 50 km.

III. Conclusion

We demonstrated error-free transmission over 100 km of negative dispersion fiber for a 10-Gb/s 1.55-μm directly modulated signal over a single fiber link without using any dispersion compensation or zero dispersion shifted fibers. To our knowledge, this is the largest distance ever reported for this kind of laser sources. Based on the high values of the achieved dispersion-length product (750 ps/nm) and our previous WDM experiments with 32 2.5-Gb/s directly modulated signals produced by different DMLs from different manufacturers, we believe that similar performance can be achieved for channels across the EDFA-bands. The results presented here are not universal since the actual performance depends on the particular DML device and its driving conditions. However, based on our previous results from the performance testing of many different DMLs produced by different manufacturers [5], [6], we believe that a negative dispersion fiber will always increase the transmission distance of 10-Gb/s DMLs. The amount of improvement will depend on the particular device and its driving conditions.

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