Characterization of 40-Gbit/s Pulses Generated Using a Lithium Niobate Modulator at 1550 nm Using Frequency Resolved Optical Gating

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Abstract—The characteristics of 40-Gbit/s pulses generated by exploiting the nonlinear characteristics of a Mach–Zender Lithium Niobate modulator are presented. A high spectral resolution frequency resolved optical gating apparatus has been developed to allow for the complete characterization of the intensity and phase of these pulses. The use of these measurements to simplify the design and optimization of an 80-Gbit/s pulse source, based on this 40-Gbit/s source followed by a nonlinear fiber compressor and multiplexer, is also demonstrated.

Index Terms—High-speed transmission, optical communications, optical pulse characterization.

I. INTRODUCTION

TO achieve multiterabit/s capacities in long-haul transport networks, it is anticipated that wavelength-division-multiplexed (WDM) systems will be upgraded to operate at line rates of 40–80-Gbit/s [1]–[4]. Optical systems operating at data rates of 40 Gbit/s and beyond place stringent requirements on the optical pulses, used to transmit the data, and the transmission fiber. At 40 Gbit/s, the effects of chromatic dispersion and the fiber nonlinearities on the transmission of the data pulses have to be carefully considered [3], [4]. It is necessary to use dispersion management techniques and/or fiber nonlinearities to counteract the deleterious transmission effects. When designing such a system, in addition to knowledge of the dispersive and nonlinear characteristics of the transmission fiber, it is essential to know the exact intensity profile and phase of the transmitted optical pulses. This is necessary since the propagation of the pulses is determined by the exact intensity and phase of the transmitted pulses together with the properties of the transmission fiber. The characterization of the chirp of an optical pulse is particularly important in dispersion compensated systems.

One compact technique for generating stable return-to-zero (RZ) data signals for 40-Gbit/s systems involves using a continuous-wave (CW) laser diode followed by a sinusoidally driven external modulator [3]. By biasing the modulator at either its null or maximum transmission point and driving it with a si-nusoidal RF signal that has a peak-to-peak voltage of twice the switching voltage of the modulator, optical pulses at twice the frequency of the applied RF signal can be generated. This technique is advantageous as it reduces the required electrical modulation bandwidth of the electro-optic modulator to 20 GHz, and it also allows for the production of carrier suppressed return-to-zero (CS-RZ) 40-Gbit/s pulse streams. The usefulness of these pulses in high-speed systems is highly dependent on the frequency chirp acquired in the modulator and the width of the pulses; thus, it is vital to accurately characterize the chirp and the pulse width.

The accurate characterization of 40-Gbit/s pulse streams such as these is challenging because they require sampling bandwidths that are greater than that provided by electrical sampling but lack the peak power and spectral bandwidth of subpicosecond pulses such as those generated by mode-locked laser systems.

Here, we demonstrate the characterization and optimization of RZ optical pulses (suitable for use in 40-Gbit/s systems) generated using a CW laser followed by a sinusoidally driven external modulator, using the technique of frequency resolved optical gating (FROG) [5], [6]. These results are also used to determine the modulator characteristics by fitting the theoretical modulator transfer function to the measured FROG trace.

We further show that the RZ pulses can be readily compressed in a nonlinear fiber compressor to produce pulses that are suitable for multiplexing to 80 Gbit/s. The design and verification of the operation of the nonlinear compressor are considerably simplified by the use of the FROG technique [7]. Subsequent multiplexing of the compressed pulses to produce a high-quality 80-Gbit/s pulse stream is also demonstrated. The second harmonic generation (SHG) based FROG apparatus that is used in these experiments has been optimized for measuring low power and low spectral bandwidth pulses such as those encountered here. Conventional pulse characterization schemes employing fast photodiodes have limited temporal resolution (picoseconds) and require different apparatus to characterize the temporal intensity, chirp and spectra. The FROG technique is advantageous as it simultaneously provides both time-dependent intensity and phase information with femtosecond resolution.

II. PRINCIPLES

The modulator used in these experiments was a single RF input balanced push–pull modulator with a separate bias elec-

trode. The envelope of the optical field at the output of the balanced modulator is given by

$$E(t) = \sqrt{P}\left[\alpha\exp\left(\frac{i\pi}{V_\pi}\left(\beta_1 V(t) + V_b\right)\right)\right.$$
$$\left. + (1-\alpha)\exp\left(\frac{-i\pi}{V_\pi}\beta_2 V(t)\right)\right] \qquad (1)$$

where P is the incident optical power, $V(t)$ the time dependent drive voltage, and V_b is the constant bias voltage. α is the power splitting (combining) ratio of the input (output respectively) Y-branch waveguide. β_1 and β_2 are the overlap factors for the RF and the optical fields in each arm of the interferometer.

The ideal nonlinear switching characteristic, of a Lithium Niobate Mach–Zender (MZ) interferometer modulator is exploited to generate the 40-Gbit/s pulse train from a 20-GHz sinusoidal drive voltage. The modulator can be used to produce both RZ and CS-RZ modulation formats. RZ operation is obtained when the modulator is biased at a peak of its switching characteristic. Overdriving it with a sinusoidal voltage between the two adjacent minima produces pulses at the zero crossings of the drive voltage. The resulting pulse repetition rate is twice that of the drive frequency.

The frequency resolved optical gating (FROG) technique developed by Delong *et al.* allows for the complete characterization of ultrashort optical pulses. The FROG measurement yields a two-dimensional (2-D) time–frequency spectrogram of the laser pulses from which the time dependent intensity and phase can be retrieved using phase-retrieval techniques [8]. Details of the numerical algorithm are found in [9]. Specifically, if the pulse electric field is expressed as $E(t) = \sqrt{I(t)}\exp[i(\omega_o t - \phi(t))]$, then the FROG technique allows for the recovery of the temporal intensity $I(t)$ and time dependent phase $\phi(t)$.

The FROG measurement technique assumes a periodicity in the input pulses. In these measurements, it is important to realize that the pulse generation process does not necessarily produce identical pulses, although the pulse trains are periodic if we consider two pulse periods. This is a direct consequence of the fact that pulses arise from different parts of the modulator switching characteristic when it is overdriven at 20 GHz. Thus, when making a FROG measurement, it is necessary to ensure that the delay is scanned over an integral multiple of two pulse periods [10]. This is in contrast to most commonly reported FROG measurements where it is assumed that all the pulses are identical (periodicity of one pulse period) and the delay is simply scanned over a range that is sufficient to completely window the pulse energy of a single pulse. The periodicity observed in the time domain will also be observed in the frequency domain of the FROG spectrogram. It is, therefore, necessary to be able to spectrally resolve this periodicity in the FROG spectrogram in both the time and frequency domains. For the pulses measured here that have a periodicity of 50 ps (two pulse periods at 40 Gbit/s), it is necessary that the spectrometer be able to resolve clearly any 20-GHz features.

The FROG measurement is not only used to determine the complex electrical field of the pulses but also to characterize the splitting ratio (α) and the overlap factors (β_1 and β_2) of
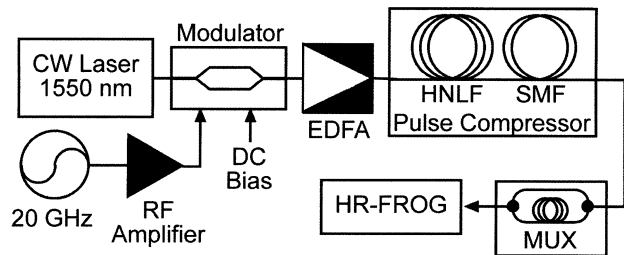

Fig. 1. 40-Gbit/s pulse generation setup based on external modulation of a CW laser. The fiber-based nonlinear pulse compressor and subsequent 80-Gbit/s multiplexer are also shown.

the modulator. These modulator parameters have a unique effect on the complex electric field of the modulator output which can be clearly seen in the FROG trace. The modulator parameters are determined by minimizing in a least squares sense the error between the experimentally measured FROG trace and the FROG trace generated from the theoretical modulator output field given by (1). The minimization is carried out using the FROG traces rather than the retrieved electric field as this is found to give better convergence. This improvement in convergence is a result of the great redundancy in a FROG spectrogram as opposed to the complex electrical field representation of the pulse, which contains no redundancy [11]. This technique also has the advantage that the retrieval of the complex field is not necessary, which reduces the error and the computation time.

III. EXPERIMENTAL SETUP

The experimental setup for the 40-Gbit/s pulse source is shown in Fig. 1. A 1538.2-nm DFB laser diode with an output power of 9 dBm is externally modulated using a 40-Gbit/s MZ Lithium Niobate modulator (JDS). The modulator has an electrical bandwidth of 30 GHz, a switching voltage $V\pi = 4.5$ V and a dc extinction ratio of 27 dB. The bias voltage and the RF power of the 20-GHz sinusoid applied to the modulator were adjusted, such that the unwanted 20-GHz components observed on an optical spectrum were optimally suppressed. The modulated optical signal was then amplified in an EDFA before being measured using the FROG technique.

The measurement of low power ($<$500-mW peak power) 2–20 ps duration optical pulses that are close to transform limited is particularly challenging due to the low nonlinear conversion efficiency and small spectral bandwidth of these pulses. To obtain good results the FROG apparatus requires a high-resolution spectrometer that has a good optical throughput. The purpose built FROG apparatus is shown in Fig. 2. The output of a computer controlled autocorrelator, based on second harmonic generation (SHG), is spectrally resolved using a specially designed Czerny–Turner type high-resolution (HR) spectrometer. The spectrometer directly images the focal spot of the fundamental beams in the SHG crystal. This configuration removes the need for the conventional entrance slit and enhances the collection efficiency. The spectrometer uses an 1800-lines/mm holographic grating and has a focal length of 1 m. The diffracted signal is detected using a 2048-pixel linear CCD array (Sony ILX511). The HR spectrometer provides a bandpass resolution of 9.5 GHz or 0.019 nm at the SHG wavelength of around 775 nm for pulses in the 1550-nm
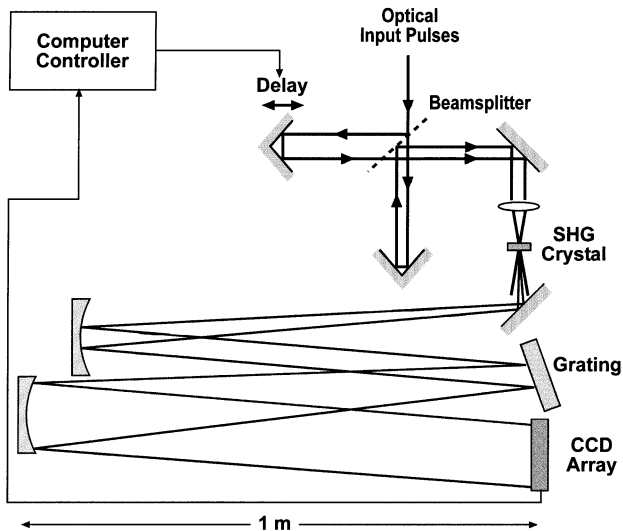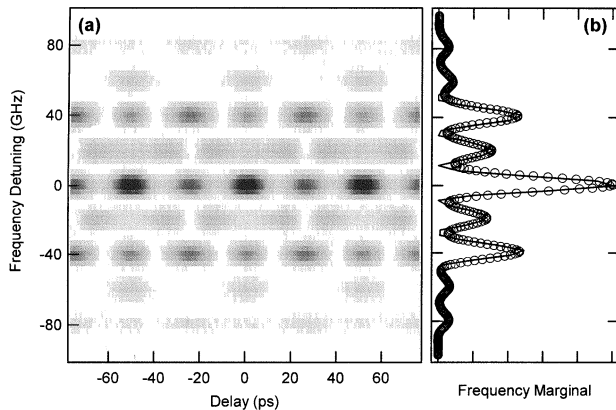
Fig. 2.   High-resolution FROG setup.

Fig. 3.   (a) Experimental FROG trace taken with nonoptimal bias conditions, the resulting 20-GHz components are clearly resolved in the FROG trace. (b) The agreement between the experimental frog frequency marginal (solid lines) and the frequency marginal calculated from the fundamental spectra (circles) is shown.

region. This FROG apparatus has a sensitivity of 500 mW^2 (FROG sensitivity is defined as the product of the minimum peak and average pulse powers at which a FROG spectrogram can be reliably obtained). This sensitivity is commensurate with optical pulses that are encountered in 1.5-μm optical communication systems.

In order to get valid retrievals and to check the integrity of the experimental FROG trace, it is essential to ensure that the experimental FROG frequency marginal and the calculated frequency marginal based on the independently measured fundamental spectra are in good agreement [11]. This is especially true when considering the undesired 20-GHz spectral components that are suppressed by at least 20 dB in the RZ case as the components of the FROG trace corresponding to these are very weak and can easily be lost in any post processing (e.g., noise filtering or thresholding).

IV. RESULTS AND DISCUSSION

Fig. 3(a) shows an experimental FROG trace taken with bias adjusted to accentuate the 20-GHz components that result

when the drive conditions are far from optimal operation. Fig. 3(b) shows the agreement between the experimental FROG frequency marginal and the frequency marginal calculated from the fundamental spectra measured on an OSA. The excellent agreement is an indication of the quality of the experimental FROG data. This result shows that the high-resolution spectrometer used in this FROG apparatus is clearly able to resolve the 20-GHz spectral components. The limited bandpass resolution of the spectrometer broadens the spectral bands that are observed in the FROG trace. To get correct retrievals the FROG trace must be physically realizable. However, while the resolution of the spectrometer is sufficient to resolve the 20-GHz components in the FROG trace, it, nevertheless, significantly broadens them from the ideal delta function shape. This problem is solved by assuming that the 40-Gbit/s RZ pulse stream has a periodicity of 50 ps such that spectral components in the FROG trace must lie on a delta function frequency comb with a spacing of 20 GHz. Thus, the raw experimental FROG trace is firstly resampled onto a 20-GHz frequency comb before the numerical retrieval process is carried out.

The experimental FROG spectrogram of the 40-Gbit/s RZ pulses was measured with a 150-ps delay sweep to ensure the windowing of six pulse periods or three times the periodicity of the pulse train. The spectrally resampled experimental FROG trace is shown in Fig. 4(a). The spectral components arising from the 40-GHz pulse repetition rate are clearly resolved by the HR FROG. The weak 20-GHz components that arise from the slight imperfections in the modulator balance and the nonoptimal operating conditions can also be seen. The signal-to-noise ratio (SNR) of this experimental FROG measurement was 15 dB and the experimental autocorrelation marginal obtained from this trace had an extinction ratio of 6.4 dB.

The FROG spectrogram reconstructed from the electric field obtained by the retrieval algorithm is shown in Fig. 4(b). The similarity between the experimental and the retrieved spectrograms indicates the quality of the retrieval. The normalized RMS FROG retrieval error for this spectrogram was 1.1×10^4. The retrieved temporal intensity (solid line) and phase (dashed line) are shown in Fig. 5(a).

The adjacent pulses are not quite identical as a result of nonoptimal operation conditions. The pulses are almost transform-limited as indicated by the linear phase across the center of the pulses and are 7.8 and 9 ps in duration. A pulse intensity extinction ratio of 16 dB was obtained. In order to check the validity of this retrieval, we compare the experimentally obtained autocorrelation marginal to the intensity autocorrelation calculated from the retrieved temporal intensity. The extinction ratio of 6.8 dB from the calculated autocorrelation is in good agreement with the directly measured extinction ratio of 6.4 dB. It should be noted however that this pulse carving technique, if the drive parameters are carefully optimized, should produce pulses with intensity extinction ratios in excess of 30 dB. This was subsequently verified with this particular modulator using real-time autocorrelation measurements. With an optimized bias and RF drive voltage, a maximum autocorrelation extinction ratio of 12 dB was observed which equates to an intensity extinction ratio of approximately 30 dB. Note that this real-time autocorrelator had a SNR of 30 dB,
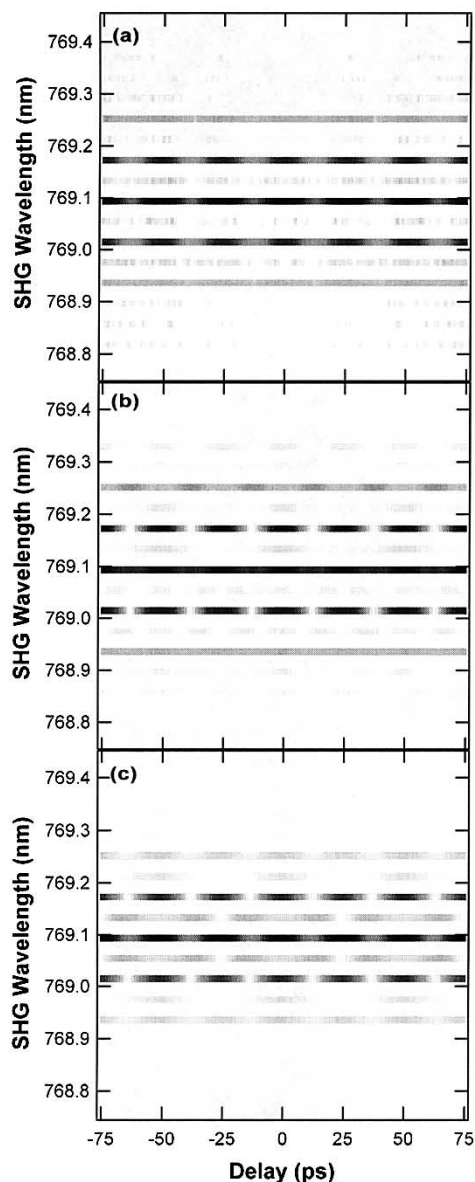
Fig. 4.   (a) Experimental, (b) numerically retrieved, and (c) theoretically fitted FROG traces for the 40-Gbit/s RZ pulses. The square root of the measured intensity is plotted to better highlight the low intensity components of the FROG trace.
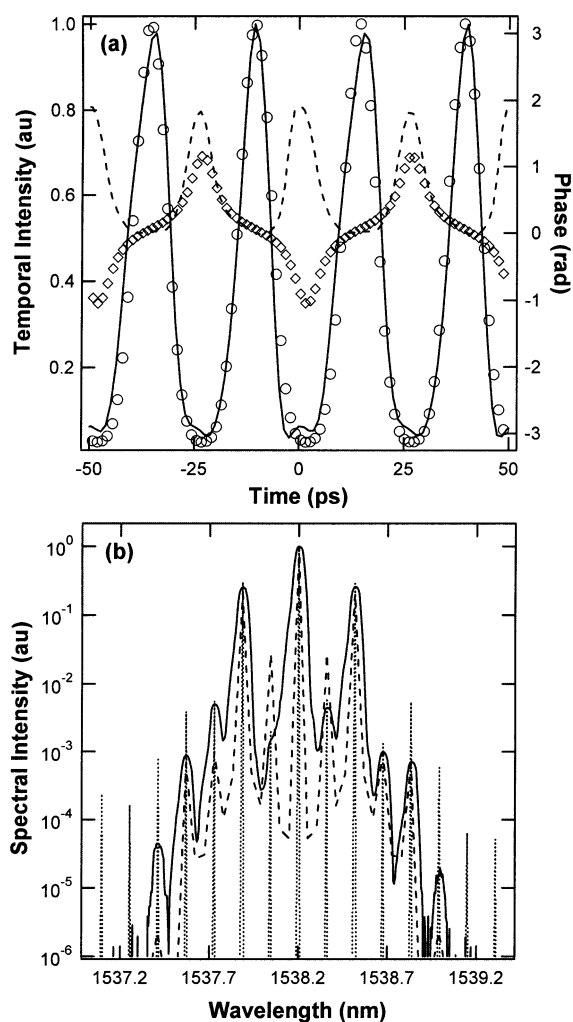

Fig. 5.   40-Gbit/s RZ pulse measurement results. (a) The retrieved temporal intensity (solid line) and phase (dashed line) is compared with the fitted theoretical temporal intensity (circles) and phase (diamonds). (b) The retrieved (dotted line) and fitted theoretical (dashed line) spectral intensity is compared with the experimentally measured spectra (solid line).

while the FROG measurements only had a SNR of 15 dB; however, this would still have been sufficient to resolve the 12-dB extinction expected in the FROG measurement under optimal drive conditions.

The retrieved spectral intensity shown in Fig. 7(b) (dotted line) also shows excellent agreement with the spectral intensity (solid line) measured using an OSA with a 0.01-nm spectral resolution. The FROG spectrogram obtained from the fitting of the theoretical modulator output field to the experimentally measured FROG spectrogram is shown in Fig. 4(c). Fig. 5(a) shows the close agreement between the retrieved and fitted temporal intensity (circles) and phase (diamonds) across the center of the pulses. However, the agreement between the retrieved and fitted phase is observed to deviate where the intensity is low this is mainly a consequence of the increased error in the determination of the phase as the magnitude of the signal approaches

zero. The spectral agreement between the retrieved and the fitted fields (dashed line) is shown in Fig. 5(b). The modulator parameters determined by this fit were $\alpha = 0.56$, $\beta_1 = 0.97$ and $\beta_2 = 0.94$ with an RMS fit error of 1.1×10^{-4} between the experimental and the theoretically fitted FROG spectrograms. It should be noted that for this modulator whose parameters are fairly close to that of an ideally balanced modulator ($\alpha = 0.5$ and $\beta_1 = \beta_2 = 1$), the features in the FROG that correspond to the deviation away from the ideal behavior are very small. Thus, the errors in the value of these parameters are likely to be significant.

The characterization of the amplitude and phase of an RZ pulse is of great value in designing lightwave systems and components since the evolution of the pulse can be modeled precisely with the aid of this knowledge. As an example of the value of the characterization of the pulses generated in our pulse carver, a nonlinear compressor was designed for the 40-Gbit/s RZ pulses to make them suitable for use in an 80-Gbit/s system. The nonlinear pulse compressor, shown in Fig. 1, consists of a length of highly nonlinear fiber (HNLF) followed by a length
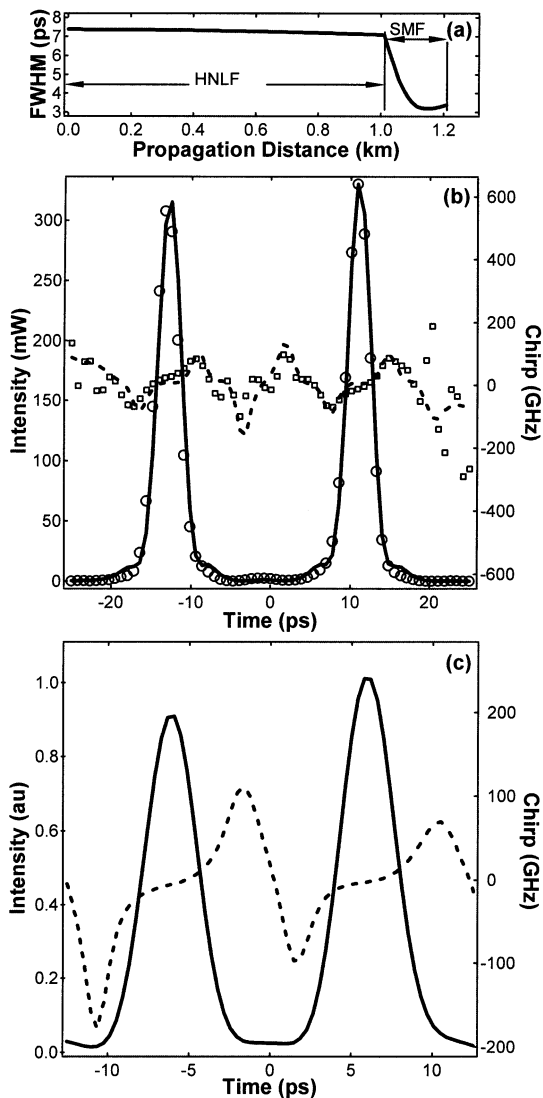
Fig. 6.   (a) Calculated evolution of the pulse width as it propagates through the compressor. This simulation is used to design the experimental compressor. (b) Comparison between the calculated temporal intensity (solid line) and chirp (dashed line) and the experimentally measured temporal intensity (circles) and chirp (squares) of the 40-Gbit/s RZ pulses after the fiber compressor. (c) Retrieved temporal intensity (solid line) and chirp (dashed line) of 80-Gbit/s pulses produced by multiplexing the 40-Gbit/s RZ pulses above.

of standard single-mode fiber (SMF). The lengths of the fibers required for the compressor were obtained from numerical simulations using the nonlinear Schrödinger equation (NLSE) and the input field obtained from the FROG measurement of the RZ pulses shown is Fig. 5(a). The optimum compressor designed to compress the 8.5-ps duration 40-Gbit/s pulses to a duration of around 3.5 ps requires 1.01 km of HNLF followed by 200 m of SMF. The evolution of the pulse width as a function of propagation distance predicted by the simulation is shown in Fig. 6(a). It should be noted that, while the minimum pulse duration of 3.2-ps is seen to occur after only 150 m, the actual length of SMF chosen was 200 m. This was because the simulations showed that this gave a better compromise between pulse width and extinction ratio, as further propagation in the SMF results in a reduction of the pedestal that is associated with the compression.

The 40-Gbit/s pulses were launched into the HNLF with a relatively modest average power of 18.9 dBm. The quality of the pulse compressor was characterized by carrying out FROG measurements on the compressed output pulses. Fig. 6(b) shows the retrieved temporal intensity (circles) and chirp (squares). Also shown in Fig. 6(b) is the calculated temporal intensity (solid line) and chirp (dashed line) based on the numerical propagation of the measured input field [Fig. 5(a)] through the designed compressor. The calculated results show excellent agreement with the experimentally measured output fields. The compressed pulses have a pulse width of 3.4 ps, and the extinction ratio is 19 dB.

In order to demonstrate the suitability of these compressed pulses for multiplexing to higher aggregate bit-rates, the compressed pulses were multiplexed in a passive fiber delay line MUX to 80 Gbit/s. The temporal intensity and chirp retrieved from FROG measurements on the 80-Gbit/s pulse train are shown in Fig. 6(c). The extinction ratio after the MUX is reduced to 16 dB due to the small pedestal that is present on the compressed 40-Gbit/s pulses.

V. CONCLUSION

A high-resolution FROG apparatus has been used to characterize the 40-Gbit/s RZ pulses generated from an externally modulated CW laser. Some degree of asymmetry between odd and even pulses generated by driving a modulator at half the repetition rate of the pulse stream is observed when the drive conditions are not carefully optimized, and this can be expected to lead to performance degradation of the system. The FROG technique is shown here to be uniquely capable of quantifying this asymmetry. This also shows that the optimization of the modulator drive parameters by observing only the optical spectrum of the generated pulse train is not sufficient to obtain optimal RZ operation. The specially designed FROG apparatus used a high-resolution spectrometer that provided a spectral resolution of 9.5 GHz. This resolution was sufficient to resolve the 20-GHz spectral components that were associated with the asymmetry.

When biased for RZ operation, the modulator produced adjacent pulses that were 7.8 ps and 9 ps in duration and virtually chirp free with an extinction ratio of 16 dB. This poor extinction ratio and the slight asymmetry in the pulses are a result of nonoptimal modulator drive conditions. The modulator characteristics derived from these measurements showed that the modulator parameters were close to the ideal design.

The design of a nonlinear fiber compressor was greatly simplified using a numerical simulation based on the retrieved electric field, both intensity and phase, from the FROG measurements. The compressor design was experimentally realized, and its performance was verified using FROG measurements. The compressed pulses were 3.4 ps in duration and after multiplexing to 80 Gbit/s had an extinction ratio of 16 dB.

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