Optimization of Optical Data Transmitters for 40-Gb/s Lightwave Systems Using Frequency Resolved Optical Gating

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***Abstract*—The measurement technique of frequency resolved optical gating has been used to optimize the phase of a 40-GHz train of optical pulses generated using a continuous-wave laser gated with an external modulator. This technique will be vital for optimization of optical transmitters to be used in systems operating at 40 Gb/s and beyond, as standard measurement techniques will not suffice to optimize such high-speed systems.**

***Index Terms*—Optical communications, optical pulse generation, optical pulse measurements, semiconductor lasers, wavelength-division multiplexing, ultrafast optoelectronics.**

I. INTRODUCTION

IN ORDER 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 Gb/s [1]–[4]. As optical systems move toward data rates of 40 Gb/s on each wavelength channel, the effect of chromatic dispersion in the transmission fiber becomes more dramatic and the use of dispersion management techniques and/or optical fiber nonlinearities to counteract the dispersive effects, must be precisely regulated [3], [4]. Regardless of the transmission technology used, in addition to knowing the dispersion parameter of the transmission fiber, it is essential to know the exact phase of the optical data signals generated at the transmitter of these high-speed systems [5]. This is necessary since the propagation of the optical data is determined by the exact intensity and phase of the optical pulses from the transmitter and the dispersion and nonlinearity of the transmission fiber. To optimize the overall performance of 40-Gb/s systems, therefore, it is vital to characterize accurately the intensity and phase of the optical data signals generated at the transmitter.

A suitable technique for generating return-to-zero (RZ) data signals for 40-Gb/s systems involves using a continuous-wave (CW) laser diode followed by a sinusoidally driven external modulator [3]. By biasing the modulator at its null point and driving it with a RF data signal with 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. The usefulness of these pulses in high-speed systems is highly dependent on the frequency chirp acquired in the modulator, and it is thus vital to accurately characterize this chirp. In this letter, we demonstrate the characterization and optimization of optical pulses (suitable for use in 40-Gb/s systems) generated using a CW laser followed by a sinusoidally driven external modulator, using the technique of frequency resolved optical gating (FROG) [6], [7].

II. EXPERIMENTAL SETUP

The 40-GHz optical pulses are generated using a 1550-nm CW laser diode followed by a sinusoidally driven external modulator. The external modulator used is a Mach–Zehnder Lithium Niobate device with a bandwidth of 30 GHz and a switching voltage of 6 V. The 40-GHz optical pulses were generated by biasing the modulator at its null point (as specified in the data sheets of the modulator) and then applying a 20 GHz sine wave to the RF input (with a peak-to-peak voltage of around 12 V). The optical pulses were then optically amplified to an average power of 10 mW (typical input power required for an optical communication system). The resulting pulses were characterized using the standard second harmonic generation (SHG) FROG technique as fully explained in [7], based on the spectral resolution of the output from a noncollinear autocorrelator. In addition, the generated pulses were measured using an optical spectrum analyzer and a 50-GHz oscilloscope in conjunction with a 50-GHz detector.

For SHG, we used a BBO crystal with an estimated interaction length of 250 μm, which provided a uniform SHG response over a 100-nm bandwidth about 1550. The SHG signal was spectrally resolved using a spectrometer with a CCD array mounted on the output. The resulting spectrogram, which is obtained from the experimental FROG setup, can then be used to retrieve the pulse intensity and phase using the FROG phase retrieval algorithm of generalized projections (GP) [7]. For all the experimental results reported below, the standard checks on the quality of the data were made, including inspection of the FROG frequency and delay marginals and comparing the spectrum and autocorrelation derived from the retrieved field with those directly measured. Pulse retrieval for the characterization carried out in this work, routinely gave low retrieval errors of $G < 0.005$ [7] with a 64×64 grid (i.e., 64 spectral and temporal points). In addition, the minimum average power for

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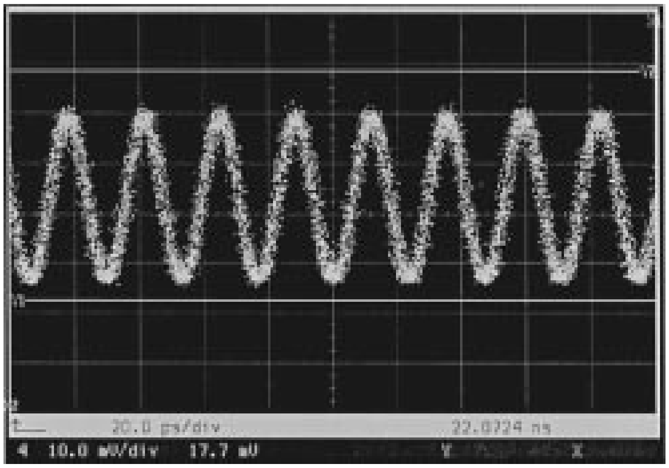

Fig. 1. Optical pulses generated using CW laser followed by external modulator and fiber amplifier and viewed using 50-GHz detector and 50-GHz oscilloscope.

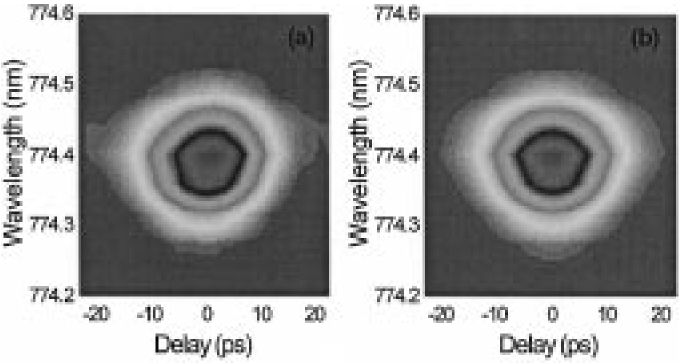

Fig. 2. (a) Spectrogram of the experimentally measured FROG trace. (b) The FROG trace generated by the numerical retrieval. Excellent agreement between the two traces can be seen.

the 40-GHz pulse stream that we could successfully measure (retrieval error kept below 0.005) with our system was around 4 mW.

III. EXPERIMENTAL RESULTS

The bias voltage and RF power applied to the external modulator were initially set to those values thought to generate optimum pulses from the setup, as deduced from the specifications of the modulator (bias voltage of 6.5 V and RF peak-to-peak voltage of 12 V). When observing the generated pulses using a 50-GHz photodiode in conjunction with a 50-GHz oscilloscope, the resulting output trace was as shown in Fig. 1. Due to the limited response time of this detection system is difficult to obtain information about the characteristics of the generated optical pulses. In addition, as the bias voltage and RF signal applied to the modulator were varied slightly, the trace on the oscilloscope did not change from a 40-GHz sinewave.

The pulses from the transmitter (consisting of CW laser gated with external modulator followed by fiber amplifier) were subsequently characterized using the FROG technique and the experimental FROG trace is presented in Fig. 2(a). The retrieved intensity and phase of the pulse is shown in Fig. 3(a). The retrieved pulse had a duration of 6.6 ps and we can clearly see that the phase of the pulse is quadratic, indicating a linear frequency shift across the pulse. The retrieved spectral width of the pulse from the FROG measurement was 0.63 nm, while independent measurements of the pulse spectrum using an optical spectrum analyzer yielded a spectral width of 0.61 nm, indicating the accuracy of the FROG measurement setup. Fig. 2(b) displays the FROG trace reconstructed using the electric field obtained from the retrieval algorithm. The similarity between the two traces in Fig. 2 indicates the accuracy of the retrieval method.

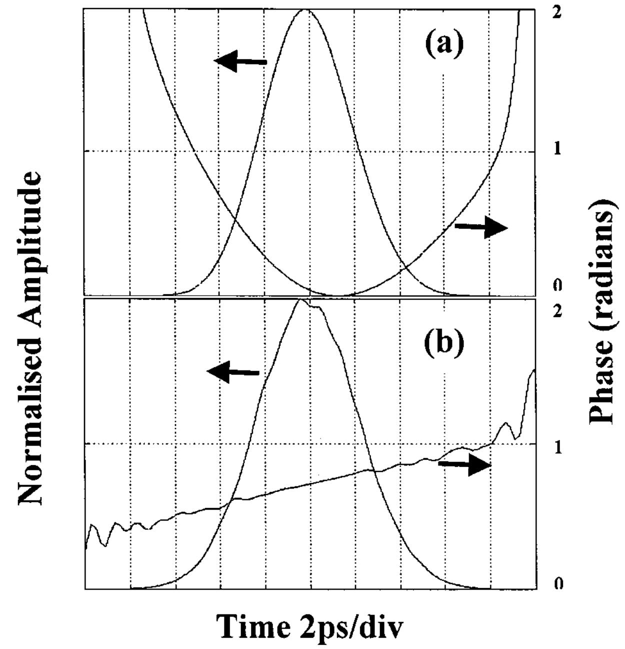

Fig. 3. Retrieved intensity (left axis) and phase (right axis) of pulses generated using CW laser followed by external modulator. (a) Pulses generated when driving conditions of modulator are not optimized. (b) Pulses generated when bias voltage and RF power applied to modulator are optimized.

To optimize the pulses generated from the modulator, followed by the fiber amplifier, we proceeded to slightly adjust both the bias voltage and RF signal applied to the modulator and characterize the resulting pulses using the FROG technique. The FROG spectrograms took approximately 40 s to acquire and the subsequent retrieval of the pulse intensity and phase took an additional minute. Using the FROG technique, we were able to determine the optimum operating point (bias voltage of 6.35 V and RF peak-to-peak voltage of 11.9 V) to generate chirp free pulses using this specific external modulator. Fig. 3(b) presents the retrieved intensity and phase of the optimum pulses that could be generated. The pulse duration was 7.3 ps and the spectral width was 0.51 nm, giving a time-bandwidth product of 0.46. As we can see, the phase is linear across the pulse indicating that it is essentially chirp free.

To further demonstrate the effectiveness of this technique, we characterized pulses generated from the external modulator when it was biased at the maximum transmission point (in order to obtain a carrier suppressed RZ signal), with the RF power applied to the modulator increased such that it was overdriven (RF peak-to-peak voltage of 16 V). In this case (Fig. 4), we can clearly see that by overdriving the modulator we develop an 80-GHz modulation on the output pulses and a quadratic

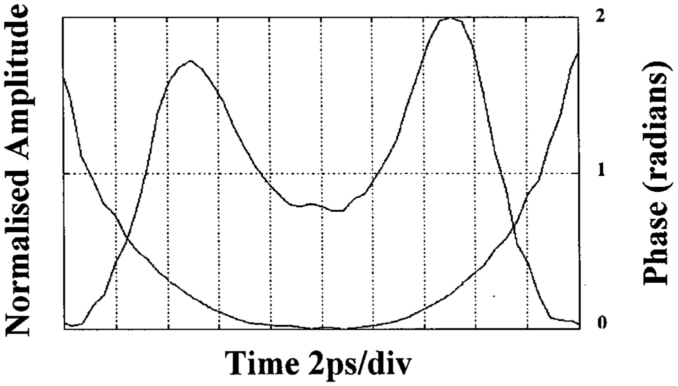

Fig. 4. Retrieved optical pulse intensity (left axis) and phase (right axis) generated from external modulator biased at maximum transmission point with RF power increased beyond optimum value such that the modulator is overdriven.

output phase. Complete characterization of this type of signal could not be achieved using direct detection followed by an oscilloscope, however, the FROG technique does allow us to completely characterize the signal. In addition, computer modeling of the pulse generation scheme has indeed demonstrated that a temporal output, as shown in Fig. 4, is obtained when the modulator is overdriven and biased at its maximum transmission point.

IV. DISCUSSION AND CONCLUSION

The accurate characterization of optical pulse sources will be vital for the development and optimization of 40-Gb/s WDM systems. Currently, the optimization of 40-Gb/s systems is achieved by examining the received bit-error rate of the signal and adjusting the optical transmitter to obtain optimum performance. However, it is clearly advantageous to be able to optimize the pulses generated at the transmitter before employing them in the overall system. In addition, if the complete intensity and phase of the data signal at the transmitter is known, then the system designers will be able to accurately model the transmission of these data signals through the fiber networks [8] and also determine the exact level of dispersion compensation and management that the system will require. In this letter, we have shown that by using the FROG measurement technique, we can retrieve the complete intensity and phase of optical pulses generated using a CW laser diode followed by an external modulator. This measurement technique has allowed us to optimize the driving conditions of the modulator in order to generate 7.4-ps chirp free pulses which would be suitable for use in 40-Gb/s WDM systems. We have also demonstrated how the FROG technique may be used to characterize more complicated pulse shapes from this pulse generation scheme

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