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Optimised pulse compression of 40 Gbit/s pulses using Frequency Resolved Optical Gating

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Abstract

The use of frequency resolved optical gating measurements to simplify the design and optimization of an 80 Gbit/s pulse source, based on a 40 Gbit/s externally modulated CW laser diode followed by a nonlinear fiber compressor and multiplexer, is demonstrated.

Introduction

To achieve multi-terabit/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].

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 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 the width of the pulses, thus it is vital to accurately characterize the chirp and pulse width.

The accurate measurement of 40 Gbit/s pulse streams such as those used in optical communications systems 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 modelocked laser systems.

Here we demonstrate the characterization and optimization of 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]. The FROG apparatus has been specially designed to enable the accurate characterization of these 2-10ps transform limited pulses. We show that these pulses can be readily compressed in a nonlinear fiber compressor to produce 3.4 ps pulses that are suitable for multiplexing to 80 Gbit/s. The design and verification of the nonlinear compressor is considerably simplified by the use of the FROG technique [7]. Subsequent multiplexing of the compressed pulses to produce a high quality 80 Gbit/s is also demonstrated. The FROG apparatus that is used in these experiments has been optimised for measuring low spectral bandwidth pulses such as those encountered here.

Experimental Setup

The measurement of low power (<500mW peak power) 2-10 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 SHG conversion efficiency in the apparatus has been improved by the use of a 1 mm BBO crystal that maximizes the nonlinear interaction length, while the specially designed spectrometer has a bandpass resolution of 0.04nm at 760nm. 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.

The experimental setup is shown in figure 1. A 1550 nm DFB laser diode with an output power of 9 dBm is externally modulated using a Mach-Zender Lithium Niobate Modulator. The modulator has a bandwidth of 30 GHz and a switching voltage of 4.5 V. The bias voltage and the RF power, of the 20 GHz sinusoid applied to the modulator were adjusted by observing the optical spectrum of the modulated source on a high-resolution optical spectrum analyzer (OSA) with a spectral resolution of 0.01 nm. The bias voltage and the RF power were adjusted such that the unwanted 20 GHz components were optimally suppressed. This occurred at a bias voltage of 4.15 V and 9 Vp-p. The modulated optical signal was then amplified in an EDFA before being measured using the FROG technique.

The experimental FROG spectrogram is shown is figure 2(a). A 50 ps delay sweep was chosen to ensure the windowing of two pulses. The spectral components arising from the 40 GHz pulse repetition rate are clearly resolved by the high resolution FROG. The FROG spectrogram reconstructed from the electric field obtained from the retrieval algorithm generated by the retrieval is shown in figure 2(b). The similarity between these two spectrograms indicates the quality of the retrieval. The retrieval error for this spectrogram was 2%. The retrieved temporal intensity and chirp are shown in figure 3. The pulses are transform-limited as indicated by the flat chirp slope across the pulse and are 7.4 ps in duration. The extinction of the CW component is also extremely good with an extinction ratio of 23 dB. The results from this FROG measurement verify that the modulator driving conditions were optimal for high-extinction transform-limited pulse generation.

The nonlinear pulse compressor consists of a length of highly nonlinear fiber (HNLF) followed by a length of standard single mode fibre (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. The fiber parameters used in the simulation are listed in table 1.

Table 1. Fiber parameters used in numerical model

Fiber	Loss (dB/km)	Dispersion (ps/nm/km)	Nonlinearity (/W.km)
HNLF	0.59	0.2	10.4
SMF	0.25	18.5	1.3

The optimum compressor designed to compress the 7.4 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 the insert to figure 1. It should be noted that whilst 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.

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 characterised by carrying out FROG measurements on the compressed output pulses. Figure 4 shows the retrieved temporal intensity (circles) and chirp (squares). Also shown in figure 4 is the calculated temporal intensity (solid line) and chirp (dashed line) based on the numerical propagation of the measured input field (fig. 3) 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 only slightly reduced to 21 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 figure 5. 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.

Conclusion

The high-resolution FROG was used to optimise and characterise the 40 Gbit/s pulses generated from an externally modulated CW laser diode. The system produced 7.4 ps chirp free pulses with an extinction ratio of 23 dB that would be suitable for use in a 40 Gbit/s WDM system. The design of a nonlinear fiber compressor was greatly simplified using a numerical simulation based on the retrieved electric field 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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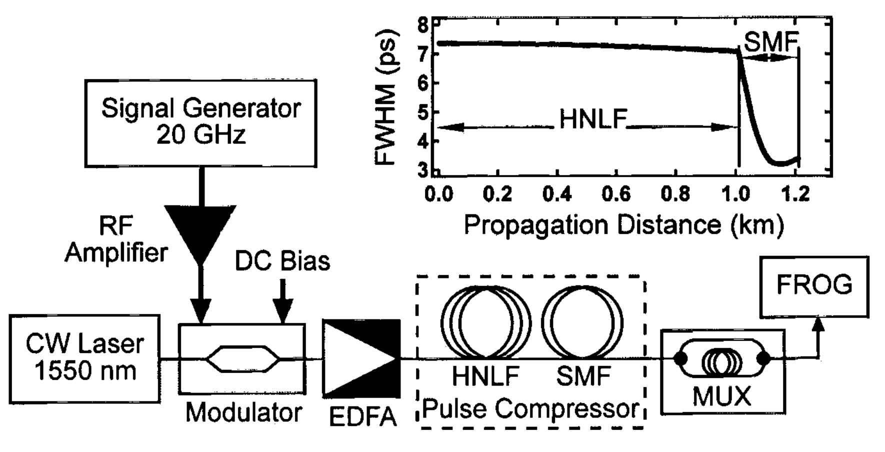

Fig. 1. Experimental Setup for generating and compressing 40 Gbit/s pulses. Insert shows the calculated evolution of the pulse width as it propagates through the compressor.

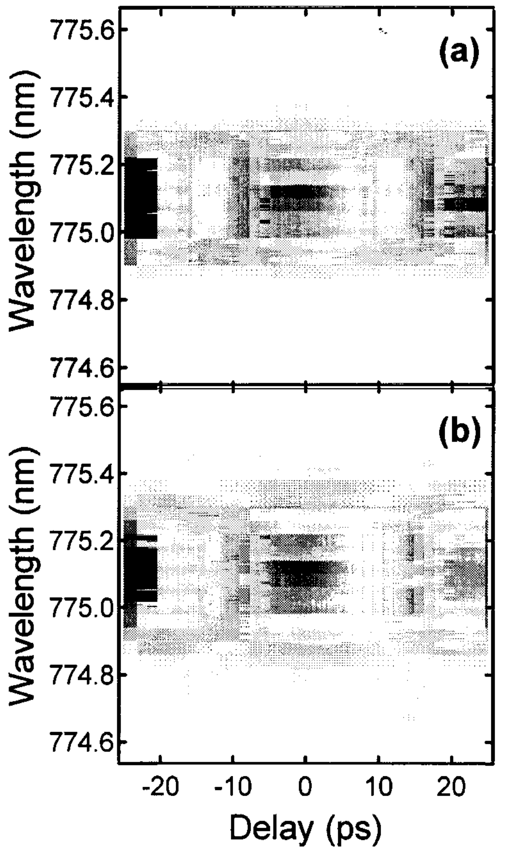

Fig. 2. (a) Experimental FROG spectrogram of 40 Gbit/s pulses directly after EDFA. (b) Calculated FROG spectrogram based on the retrieved electric field.

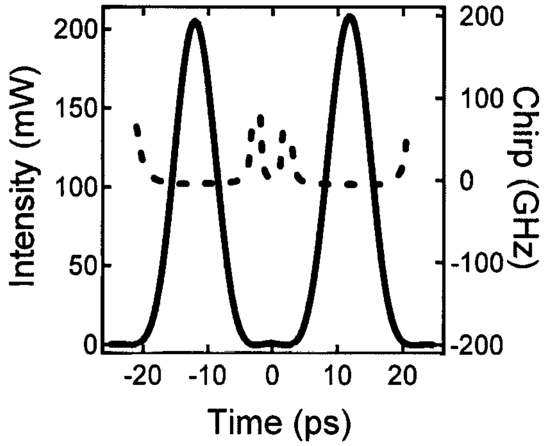

Fig. 3. Retrieved temporal intensity (solid line) and chirp (dashed line) of 40 Gbit/s pulses directly after EDFA.

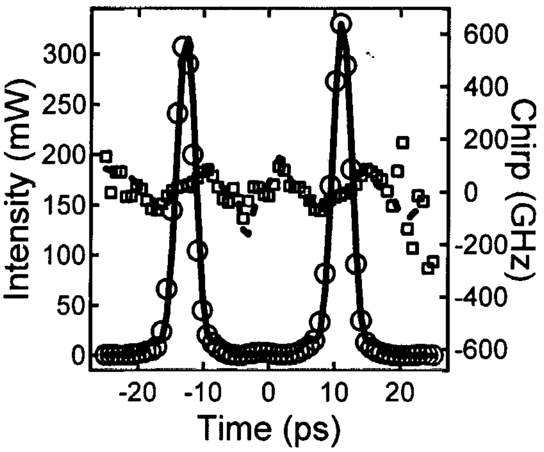

Fig. 4. Comparison between the calculated temporal intensity (solid line) and chirp (dashed line) and the experimentally measured temporal intensity (circles) and chirp (squares) of the 40 Gbit/s pulses after the fiber compressor.

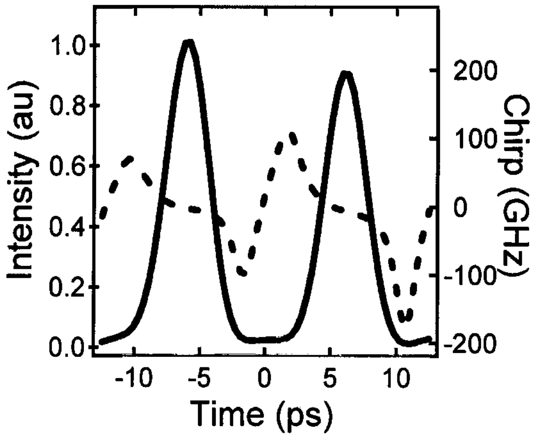

Fig. 5. Retrieved temporal intensity (solid line) and chirp (dashed line) of 80 Gbit/s pulses after the MUX.