



## Non-uniformly Spaced, Low Time-jitter, Quasi-Fourier Transform Limited Optical Short Pulse Generation from Gain-switched Laser Diode Aiming for Optical Sampling Based on Generalized Sampling Theorem

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**Abstract:** In this paper, for optical sampling based on the generalized sampling theorem, non-uniformly spaced, low time-jitter, quasi-Fourier transform optical short pulse generation from a gain switching laser diode (GS-LD) is investigated. Proof-in-principle experiments showed that precise control of carrier density in a GS-LD, namely the use of precisely tailored driving current, made generation of non-uniformly spaced optical pulses possible. Further precise tailoring of the driving current enabled the control of the non-uniformly spaced optical short pulses, i.e. the number of successive pulses in a pulse group, pulse interval in a pulse group, and the pulse group period. Amplitude enhancement, RMS time-jitter reduction, and pulse shortening by introducing self-seeding, optical band-pass filtering, and dispersion compensation are also reported. As a result, non-uniformly spaced optical short pulse generation including twin/triple pulses with 25 ps of the full-width half the maximum, 2.5 ps RMS time-jitter, and 500 ps pulse interval has been experimentally demonstrated.

**Keywords:** Optical sampling, Generalized sampling theorem, Non-uniformly spaced optical short pulses, Gain-switching, Self-seeding, Time-jitter.

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### 1. Introduction

High-speed analog-to-digital conversion (ADC) technologies are significant in this digital era, but the technological advancement is being saturated and a breakthrough is expected. Optical ADC technologies [1] are widely studied to cope with the issue, but all of the conventional reports are based on uniformly-spaced sampling following the low-pass sampling theorem. Many researchers have actively discussed on “compressed sensing” or “sparse sampling” to reduce sampled data or sampling frequency for “sparse” signals in some sense [2]. The generalized sampling theorem (GST) [3] is one of such efforts and it enables

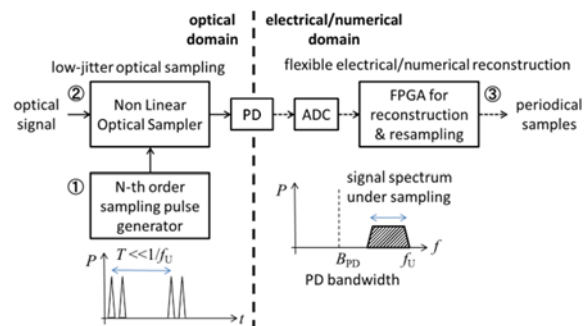
bandpass sampling of signals by non-uniformly spaced samples. At the best of our knowledge, there is no previous study on optical sampling based on the GST. This is because optical sampling requires nonlinear phenomena based on optical short pulses but optical short pulse generators are able to generate uniformly spaced pulse train in general. The easiest way to have a non-uniformly spaced optical short pulse train is a time division multiplexing (TDM) configuration using an optical splitter, an optical delay lines precisely controlled relative time delays, and an optical coupler, however, such a bulky configuration is not attractive at from the view point of tenability, system foot print and cost. This paper provides the first

report on the generation of non-uniformly spaced optical short pulse train for the sampling pulse generator in the optical sampling based on the GST.

Here, gain-switching in a distributed feedback laser diode (DFB-LD) is utilized as the base technology for the non-uniformly spaced optical short pulse generator, and a specially tailored LD driving current for precise carrier density control, self-seeding for time-jitter reduction [4] and an optical bandpass filter (OBPF) and a dispersion compensation fiber (DCF) for pulse shortening [5] are introduced. This paper is an extended version of the conference paper [6] presented in the 1<sup>st</sup> Optics and Laser conference held in Barcelona, Spain in May, 2018.

## 2. Non-uniformly Spaced Optical Sampling Based on Generalized Sampling Theorem

Fig. 1 shows a brief block diagram of the non-uniformly spaced optical sampling based on the GST. The numbers in the figure shows three fundamental functions of the non-uniformly spaced optical sampling technology, i.e. (1) a non-uniformly spaced optical short pulse generator, (2) a nonlinear optical sampler based on some kind of nonlinear optical effect such as four-wave mixing (FWM) or cross-phase modulation (XPM) and so on, (3) a digital signal processing unit for signal reconstruction or processing. Since the second and the third function block is common with the typical optical sampling systems, this paper only treats the first function, the non-uniformly spaced optical short pulse generator.

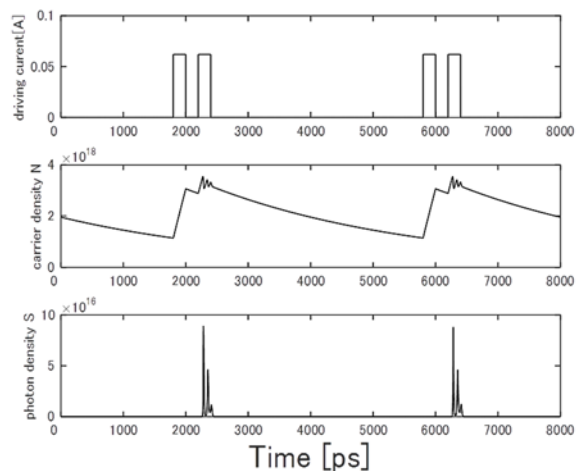


**Fig. 1.** Optical sampling system based on the generalized sampling theorem.

At the bottom right of Fig. 1, a spectrum model of a bandpass signal is shown. As the maximum frequency is  $f_U$ , the sampling frequency  $f_s$  in following the lowpass sampling theorem is equal to or greater than  $2f_U$ . However, since the signal is “sparse” in the spectrum domain, the sampling frequency is determined not by the maximum frequency  $f_U$  but by the bandwidth of the signal when one follows the GST, and it can be drastically reduced than  $2f_U$ .

## 3. Basic Strategy to Generate Non-uniformly Spaced Optical Short Pulses from GS-LD

To generate non-uniformly spaced optical short pulses from a GS-LD, a driving current must be tailored thoughtfully. Fig. 2 shows a numerical analysis result of a GS-LD being fed two successive driving current pulses intending to generate a non-uniformly spaced optical short pulse train. The top and bottom of the figure are the driving current and photon density, respectively. As clearly shown in the figure, supplying the driving current pulses only for the pulse oscillation is not sufficient, therefore additional driving signal to control the carrier density in the gain medium of the DFB-LD is required prior to the pulse oscillation.



**Fig. 2.** Numerical results for a GS-LD being fed two successive driving current pulses.

The purpose of this work is to generate not randomly spaced optical short pulses but periodically spaced optical pulse groups which seem like a non-uniformly spaced optical pulse train. The key point is how to tailor the carrier density in a gain medium of a GS-LD just before the oscillation of the first optical short pulse in a pulse group. Fig. 3 shows a basic concept of the proposed non-uniformly spaced optical short pulse generation from a GS-LD. In the figure, a pulse group interval  $T$  is divided into three sections: A: spontaneous emission duration, B: carrier accumulation duration, and C: pulse oscillation duration. In the spontaneous emission duration, the carrier density of the gain medium decreases in time and it causes insufficient carrier density for optical pulse oscillation. Therefore, in the carrier accumulation duration, the carrier density in the gain medium is raised to a level sufficient for optical pulse oscillation in the pulse oscillation duration. Though the driving current in the carrier accumulation duration is shown as the successive short rectangular pulses in Fig. 3, any waveforms may be accepted.

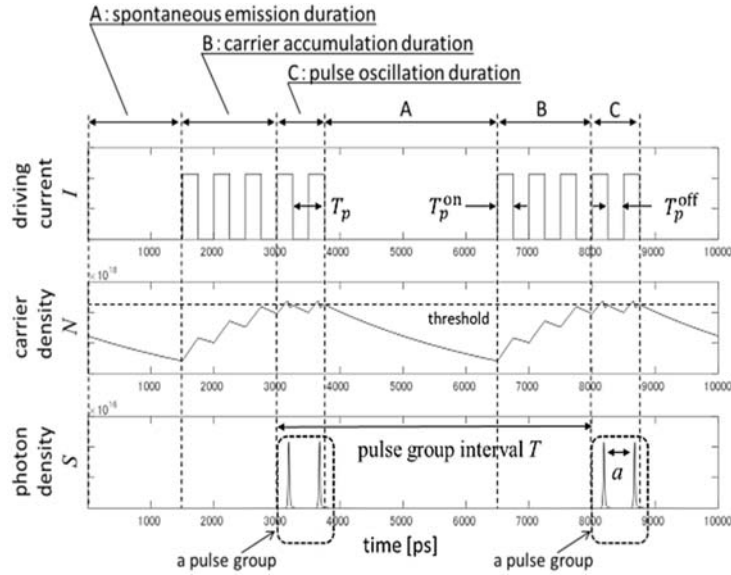


Fig. 3. Basic concept of non-uniformly spaced optical short pulse generation from a GS-LD.

#### 4. Numerical Evaluations on Non-uniformly Spaced Short Pulse Generation by Solving Carrier-rate Equations

To confirm the effectiveness of the basic concept described above, numerical evaluations were carried out by solving the following carrier-rate equations,

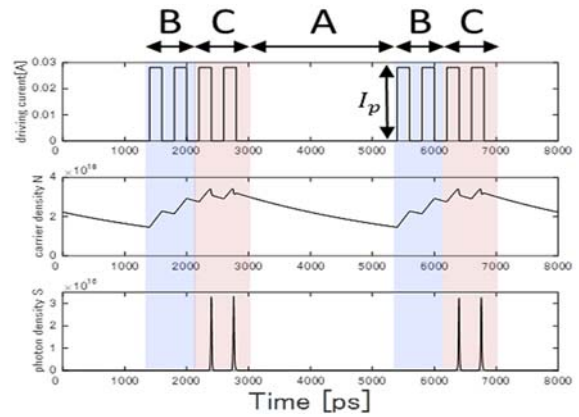
$$\begin{cases} \frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_s} - \alpha(N - N_0)S \\ \frac{dS}{dt} = \alpha(N - N_0)S - \frac{S}{\tau_{ph}} + \beta \frac{N}{\tau_s} \end{cases}, \quad (1)$$

where  $I$ ,  $N$ , and  $S$  are the driving current, the carrier density in the gain medium, and the photon density, respectively. In the numerical evaluations, we used rectangular short pulse train as the driving current signal in the carrier accumulation duration, and the pulse width and the pulse amplitude were the same with the ones in the pulse oscillation duration.

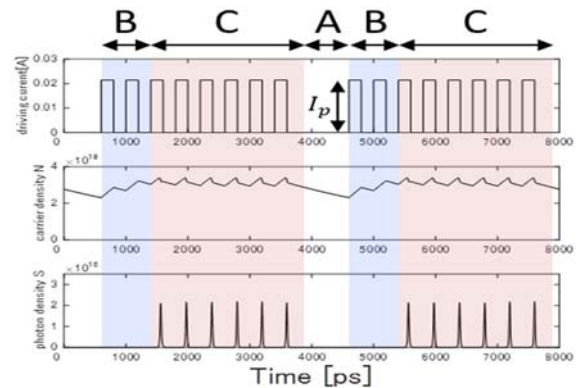
Fig. 4 and Fig. 5 shows the numerical results. As clearly seen from the figures, by tailoring the driving current adequately, the non-uniformly spaced optical short pulse trains are generated and the parameters of the generated optical pulses, namely the number of optical pulses in a group (Fig. 4(a) and (b)), the pulse interval (Fig. 5(a)), and the pulse group interval (Fig. 5(b)) could be controlled as intended. The difference in the peak amplitudes of the driving current signals should be noticed.

There were mainly three parameters used to tailor the driving current in the numerical evaluations; the number of driving current pulses in the pulse oscillation duration  $C$  for controlling the number of the generated optical short pulses in a pulse group, the

driving pulse period  $T_p = T_p^{\text{on}} + T_p^{\text{off}}$  for the optical short pulse interval, and the pulse group interval  $T$ .



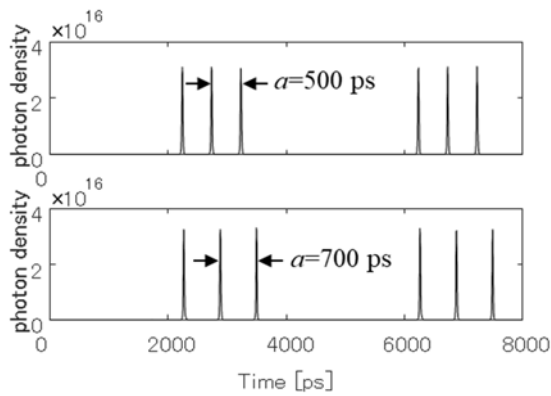
(a) two pulses in a pulse group



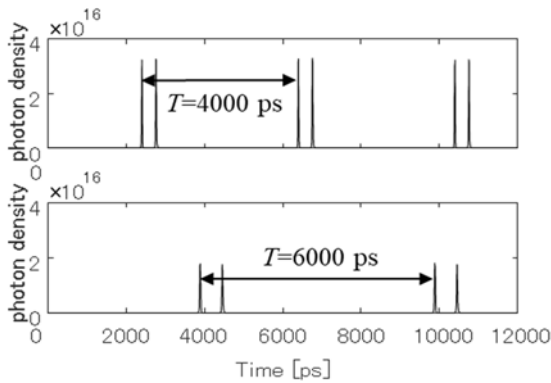
(b) six pulses in a pulse group

Fig. 4. Numerical results for the different number of pulses in a pulse group.

$$T_p = 400 \text{ ps}, T_p^{\text{on}} = T_p^{\text{off}} = 200 \text{ ps}, T = 4000 \text{ ps}.$$



(a) With different pulse interval



(b) With different pulse group interval

**Fig. 5.** Numerical results for the different pulse interval and pulse group interval.

Notice again that only the important point is the carrier density level just before launching the driving current pulse for optical pulse oscillation. As the driving current pulses were the same both in the carrier accumulation and pulse oscillation durations, the peak current  $I_p$  had to be tuned to obtain the desired carrier density just before launching the driving current pulses for optical pulse oscillation.

## 5. Quasi-Fourier-transform-limited Pulse Generation from GS-LD

In a gain medium of a GS-LD, accumulation of carrier density by injection current fluctuates due to noise, resulting in wobble of oscillation timing called time-jitter. The self-seeding scheme [4] uses optical feed-back of some part of generated optical pulses to regularize pulse oscillation timing in the gain-medium. The carrier density in the gain-medium is forced to exceed an oscillation threshold for the avalanche effect because of the optical feed-back. Therefore pulse oscillation timing could be regulated and the time-jitter be suppressed by setting the amount and timing of the feed-back adequately. Items required to realize this concept are a gain-medium such as a distributed feed-back laser diode (DFB-LD) without

an isolator in its casing, an optical delay line with a proper length, and a partial reflector with a proper reflectivity. The self-seeding scheme requires small injection current, resulting in small pulse amplitude and rather wide pulse width more than 30 ps. When injection current is increased, a long pedestal follows after the first short pulse generated by the relaxation oscillation. This pedestal is due to wavelength chirp and pulses generated from a GS-LD are not Fourier transform limited in general.

Chen, *et al.* proposed the use of optical narrowband filter to reduce wavelength chirp of pulses with pedestal from GS-LDs [5]. On the contrary to the GS-LDs with self-seeding, it requires rather large injection current to have large pulse amplitude and narrow pulse width. By such large injection current, the first pulse by the relaxation oscillation has a narrow pulse width and high peak but it is followed by a long pedestal due to wavelength chirp. The leading high peak pulse and the long pedestal consist of different wavelength components and the pedestal has longer wavelength components than the leading high peak pulse; thus by cutting-off the longer wavelength components in wavelength region by a sharp optical bandpass filter, only the leading pulse with narrow pulse width and high peak could be obtained. Moreover, the larger the injection current is, the less the time-jitter, comparing with a fundamental GS-LD scheme without any additional equipment. However, the amount of the time-jitter reduction due to increased injection current is not enough for many applications and a combination with the self-seeding scheme is preferred

Fig. 6 shows the experimental setup for preliminary experiments of the proposed quasi-Fourier-transform-limited optical short pulse source combining above two schemes. To make tuning of optical delay line length between the gain-medium and the partial reflector easy, a narrowband optical band pass filter (OBPF) was placed after the optical isolator. In this preliminary experiment, fundamental uniformly-spaced pulse generation was carried out. The repetition rates of optical pulses were chosen at 5 patterns: 0.5, 0.8, 1.0, 1.25, 2.5 GHz. The relationship between temporal pulse width and spectral bandwidth, full-width measured at -30 dB from the spectral peak, of the generated pulses are plotted in Fig. 7. The open marks are for the proposed scheme and the filled marks are for the GS-LD with self-seeding only. Clearly, the generated pulses by the proposed scheme are closer to the line showing the Fourier-transform limit and it is confirmed that the generated pulses are quasi-Fourier-transform-limited. The shortest optical pulse width of 10.28 ps was obtained at 0.8 GHz of the repetition rate, while the lowest chirp of 0.13 nm was observed at 2.5 GHz. Fig. 8 shows optical spectra and temporal waveforms for both the proposed scheme and the self-seeding only. At both repetition rates of 0.8 GHz and 2.5 GHz, shorter optical pulses preserving small time-jitter could be obtained by spectral slicing of the longer wavelength component.



Fig. 6. Preliminary experimental setup for Quasi-Fourier transform-limited pulses generation.

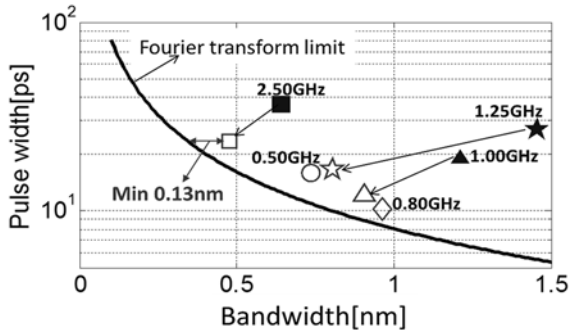


Fig. 7. Temporal pulse width vs. -30dB spectral bandwidth.

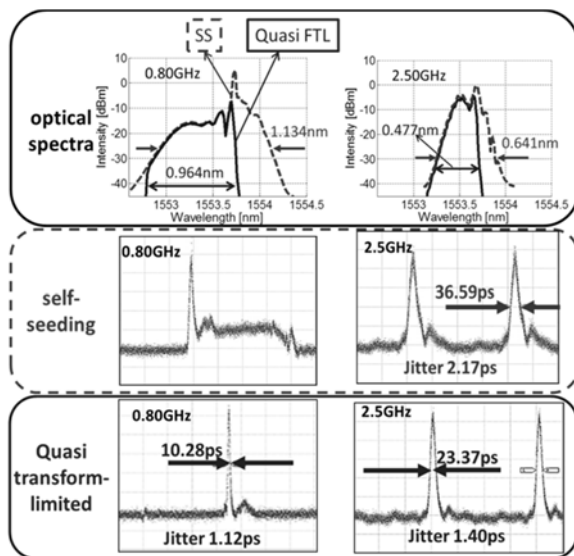


Fig. 8. Comparison of optical spectra and temporal waveforms for both the self-seeding only and the proposed schemes.

## 6. Proof-in-principle Experiments for Non-uniformly Spaced Optical Short Pulse Generation Using GS-LD

From the viewpoint of carrying out experiments, the dependent relationship of the driving current signals both the carrier accumulation and pulse oscillation duration described in the above section is not preferred since  $I_p$  affects the quality of the optical short pulses itself too, namely intensity, pulse width or waveform generated; thus a different waveform for the driving current signals were chosen for the experiments. We used a rectangular pulse with relatively low amplitude and a longer duration than the driving pulses in the pulse oscillation duration to

control the carrier density in the gain medium precisely and independently. See Fig. 9 for the brief waveform of the driving current signals

Fig. 10 shows the setup for the proof-in-principle experiments. To tailor the driving current signal, an arbitrary waveform generator, Tektronix AWG7122C, was utilized. A customized DFB-LD module without a built-in isolator, a diamond-carbon-coated special optical connector with a partial reflectivity of 0.4 % and an external optical isolator were used for the time-jitter reduction by self-seeding. Also, an OBPF (santec, OTF-350) was placed after for pulse shortening by pulse chirp truncation.

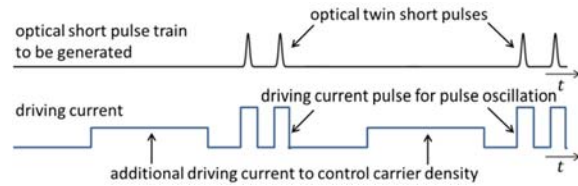


Fig. 9. Driving current waveform used in the experiments. The carrier accumulation was done by one wide width, low amplitude pulse.

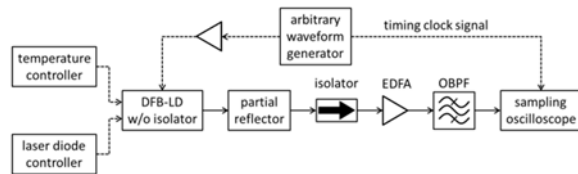
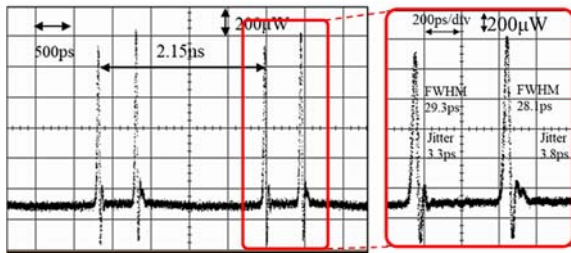


Fig. 10. Experimental setup.

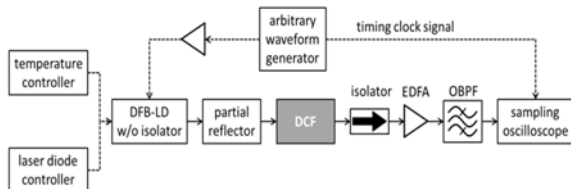
Fig. 11 shows the resultant non-uniformly spaced, quasi-Fourier-transform limited optical short pulses. The FWHMs (full-width-at-half-the-maximum) were 29.3 ps and 28.1 ps, the RMS time-jitters were 3.3 ps and 3.8 ps for the first and the second pulses, respectively. Also, the pulse interval in a pulse group and the repetition rate of the pulse groups (the inverse of the pulse group interval) were 500 ps and 512.5 MHz, respectively. Although there is a difference between amplitudes of the generated twin pulses, it can be controlled by slightly modifying the driving current signal amplitude. The RMS time-jitter was more than 7 ps without the self-seeding, and the FWHM was more than 40 ps without the OBPF. These facts mean that, even in the non-uniformly spaced optical pulse generation, the fundamental process of the gain-switching is maintained; therefore any other techniques to obtain the better quality of optical pulses by GS-LD may be applied. In our proof-in-principle experiment, we had to tune pulse group repetition rate precisely by controlling the period of the driving current. This was done for the time-jitter reduction by the self-seeding. When one needs to have an arbitral pulse group period, an optical delay line could be placed between the DFB-LD and the partial reflector. Even in that case, the proposed scheme is much easier

than the TDM configuration since only one delay line is enough for any number of pulses in a pulse group.



**Fig. 11.** Observed waveform of non-uniformly spaced optical short pulses.

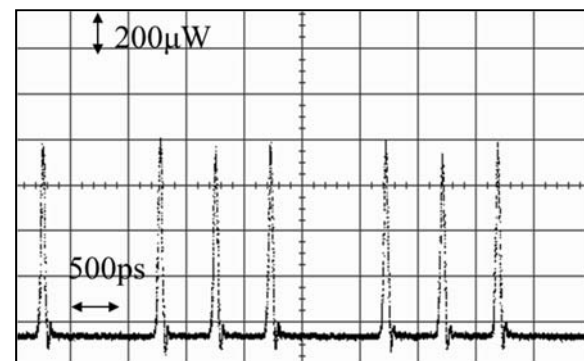
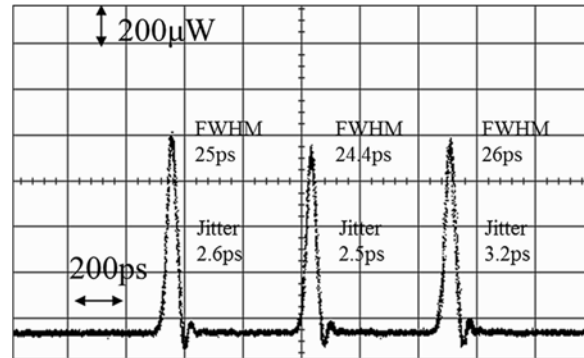
To generate shorter and more stable optical pulses, a DCF of one-kilometer length was inserted between the isolator and the EDFA. The DCF was inserted just after the partial reflector for the self-seeding to make tuning easy. The triple pulses generated from the setup are shown in Fig. 13. The FWHMs of the generated optical pulses are around 25 ps. However, the values of the measured FWHMs are not correct since the bandwidth of the photo-detector and the sampling oscilloscope used in the experiments were 40 GHz and 50 GHz respectively, and were not enough for the generated optical short pulses. When we measured the FWHM of the uniformly spaced optical short pulses from the same GS-LD before by using a borrowed optical sampling scope with a measuring bandwidth of 160 GHz, the FWHM was around 10 ps when we used both the OBPF and the DCF; therefore the actual FWHMs of the pulses shown in Fig. 13 is estimated as around 10 ps.



**Fig. 12.** Experimental setup with a dispersion compensation fiber of 1 km for pulse shortening.

Finally, the applicability of the proposed non-uniformly spaced optical short pulses from a GS-LD as a sampling pulse source of optical sampling is discussed. In the reference [6], Nogiwa, *et al.* reported optical sampling using optical short pulses from a GS-LD and the FWHM, the time-jitter, the amplitude of the optical short pulses, and the time-jitter to the FWHM ratio are 0.9 ps, 0.2 ps, 1 mW, and 22 % respectively. On the other hand, those values for the proposed non-uniformly spaced optical pulses from a GS-LD, for example in the case of Fig. 9, are 25 ps, 2.5 ps, 0.8 mW, and 10 % respectively. While the pulse width of our results is not short enough as in [7],

the amplitude is similar and the time-jitter to the FWHM ratio is halved. In the reference [8], Nonaka, *et al.* have reported generation of optical short pulses with the FWHM of 1.9 ps from a similar GS-LD with self-seeding by optimizing the characteristics of the DCF. This report encourages us to proceed further realizing a full system experiment for the optical sampling based on the GST.



**Fig. 13.** Triple pulses using a DCF of 1 km length. The upper figure is for a zoomed waveform in a pulse group and the lower is for wider time span.

## 7. Conclusion

In this paper, non-uniformly spaced, low time-jitter, and quasi-Fourier-transform limited optical short pulse generation directly from a GS-LD was reported for the first time. Precise control of carrier density in a GS-LD, namely the use of precisely tailored driving current, made the direct generation of non-uniformly spaced optical pulses from the GS-LD possible. The self-seeding scheme and an OBPF help to reduce time-jitter and wavelength chirp, resulting in optical short pulses with better quality. The proposed method enables the direct generation of non-uniformly spaced optical short pulse trains which are applicable to the optical sampling based on the GST without using a bulky, cumbersome to tune, and cost-ineffective TDM configuration.

Flexible control of the generated optical pulses and further improvements in pulse quality are required to realize non-uniformly spaced optical sampling based on the generalized sampling theorem.

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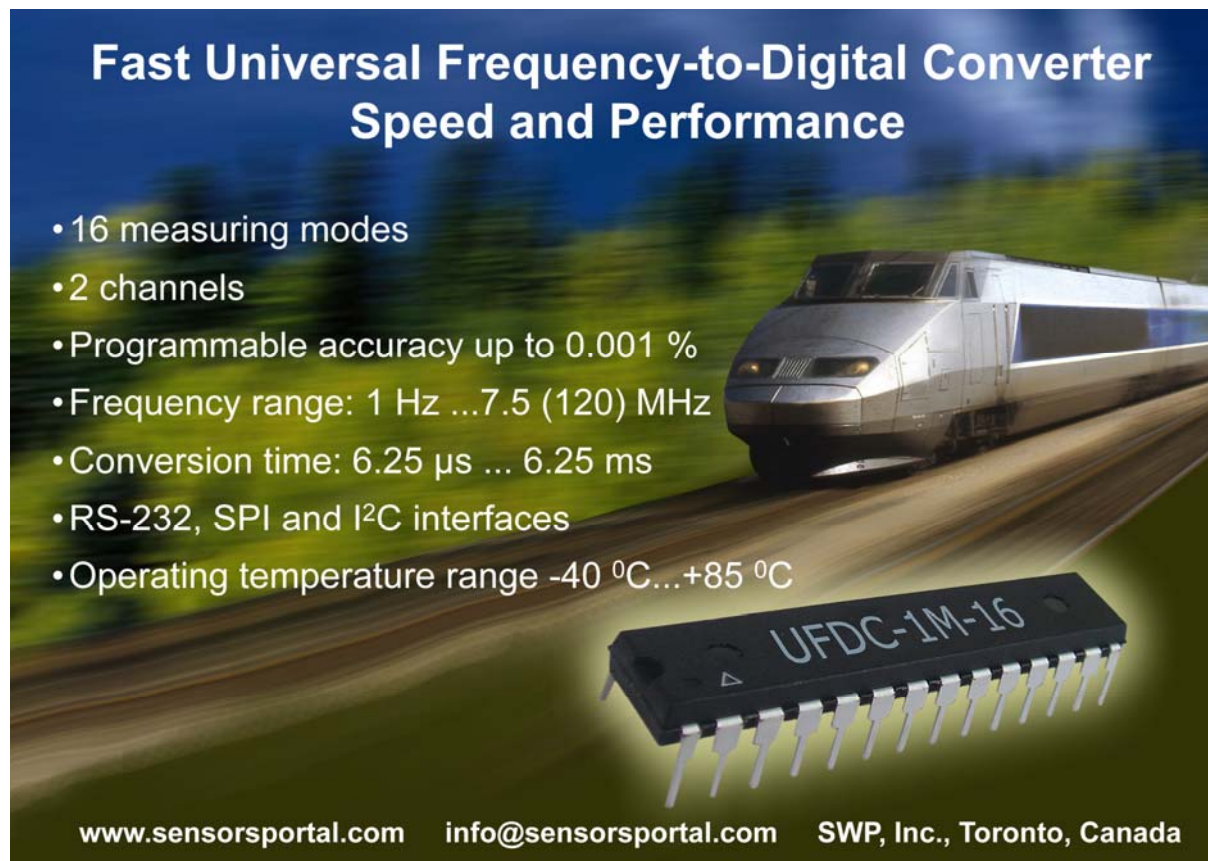
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