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ARTICLE

Pedestal Free Pulse Source for Ultrahigh Data Rate Optical Time Division Multiplexing Systems Self-Phase Modulation Based

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In this paper, an ultra-short (0.95 ps) pedestal free pulse source is optimized for ultrahigh data rate optical time-division-multiplexing (OTDM) systems. This source is based on a dispersion-compensation stage using a single-mode fiber (SMF) followed by a simple fiber-based pulse compression stage (using comblike dispersion profiled fiber (CDPF) and a self-phase modulation (SPM) based reshaping stage. A stable operation, with a high extinction ratio of 81 dB and a remarkable timing jitter of 72 fs are successfully achieved. Source tunability is available over the wavelength range 1546–1561 nm with a high quality pulse shape of 0.475 time bandwidth product. A noteworthy behavior of multiplexing from 10 to 320 Gb/s is observed. A comparison between this work and related literature is carried out showing an appreciable improvement.

Keywords: OTDM, DC, SPM, CDPF, HNLF, DCF, PM, MZM.

1. INTRODUCTION

The achievement of high-speed optical time division multiplexing (OTDM) in optical fiber transmission systems is significant to get over the electronic bottleneck. Recently, OTDM-transmission technique has made a lot of progress toward much higher bit rates and longer transmission distances.[1]

In OTDM systems, generation of an ultrahigh-quality pulse sources with 10 to 40 GHz repetition rates is an essential requirement.[2] Pulse source for the OTDM applications needs to achieve a number of requirements: (i) tunability in both repetition rate and wavelength, (ii) ultra-short duration (in the range of picoseconds), (iii) stable operation, (iv) low timing-jitter, (v) simple source design architecture, and (vi) high extinction ratio (ER).[3,4]

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Several literature designs evaluate and optimize different pulse sources to meet the previous requirements for OTDM applications. A 1.1 ps short pulse has been generated successfully in Yang et al.[5] but, the electro-absorption modulator (EAM) induces a large loss that degrades the ER and provides unstable operation. In Hu et al.,[6] a 1.6 ps pulse with a 84 fs timing jitter was generated using one phase modulator (PM) and a distributed feedback (DFB) laser diode, but the large pedestal makes it unpractical for ultrahigh-speed multiplexing applications such as OTDM. MachZehnder Modulator (MZM) can be an optimum substitution for the EAM and can eliminate its drawbacks. Therefore, a 1.4 ps pedestal-free pulse source using commercial cascaded MZM and fiber-based compressor with 132 fs timing jitter was achieved in Chen et al.[7] But, 1.4 ps pulse width and the timing jitter still should be improved to be more suitable for ultrahigh-speed OTDM specifications. A pulse source with a remarkable pulse width of 680 fs, low timing jitter and ER is designed in Hu et al.[3] This source is based on PM and self-phase modulation (SPM). Although this design has previous remarkable achievements, but it suffers from a relatively complex design.[3]

In the present work, a stable and tunable 10 GHz ultrashort pulse source that utilizes PM and MZM is optimized. The main stages in the system design include a dispersion compensation (DC) unit, a nonlinear pulse compression unit and a nonlinear pulse reshaping unit. A high quality

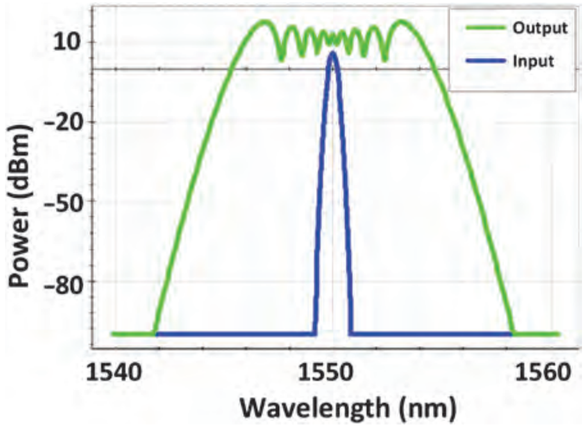

Fig. 1. Signal pulse spectrum at the input (blue) and output of a HNLF (green).[8]

pulse shape with low pulse width and pedestal-free operation is generated. A lower timing jitter, high ER and a simple pulse source design is achieved. This results in an improved performance for multiplexing up to 320 Gb/s which indicates a very good potential for application in ultrahigh-speed OTDM systems. A useful comparison with the previous work provides the figure of merits of this work.

The rest of this paper is organized as follows: Physical concept of SPM and the general pulse source design and the simulation setup, parameters and values for the proposed pulse source are presented in Section 2. Section 3 present Simulation results, discussion and OTDM pulse source specifications verification. More details about previous work related to design and evaluation of pulse sources suitable for OTDM applications followed by a comparison between the obtained results in this work with the previous work are presented in Section 4. Section 5 is devoted for the main conclusions.

SPM is the main technique for realizing two essential stages of the pulse source (in pulse reshaping stage and sometimes in pulse compression stage) as will be presented in Section 5.

Figure 1 illustrates a broadened spectrum that occurs due to SPM nonlinearity in optical fibers. A signal pulse propagates through high nonlinear fiber (HNLF). The amount of spectral broadening caused by SPM is affected greatly (and can be controlled) by the power level of the input signal.[8,9]

The spectral width for a Gaussian input pulse is given by:

$$\Delta\omega_{\rm SPM} \sim \Delta\omega_0 \gamma P_0 L_{\rm eff} \quad (1)$$

where $\Delta\omega_0$ and P_0 are the initial spectral width and peak power of the input signal pulse, respectively. γ and $L_{\rm eff}$ are the HNLF nonlinear coefficient and effective length, respectively.

A famous design architecture that can be used in realizing an effective pulse source for OTDM applications is shown in Figure 2. First, an initial pulse is generated by a DFB laser diode together with an EAM or PM.[5,6] An alternative is generating the initial pulse using a continuous wave (CW) light source, together with a MZM and PM.[3,7] The second stage is the DC that utilizes a dispersion-compensation fiber (DCF) or single mode fiber (SMF).[5] The third stage is a pulse compression stage that consists mainly of an erbium-doped fiber amplifier (EDFA) and a HNLF or an EDFA together with a comblike dispersion profiled fiber (CDPF).[3,5–7] The pulse reshaping is the final stage and is accomplished mainly by an EDFA, a HNLF and optical band-pass filter (OBPF).[3,5–7]

2. SIMULATION SETUP AND PARAMERS

The Optisystem is used to design and simulate the proposed system. The proposed design of the short pulse

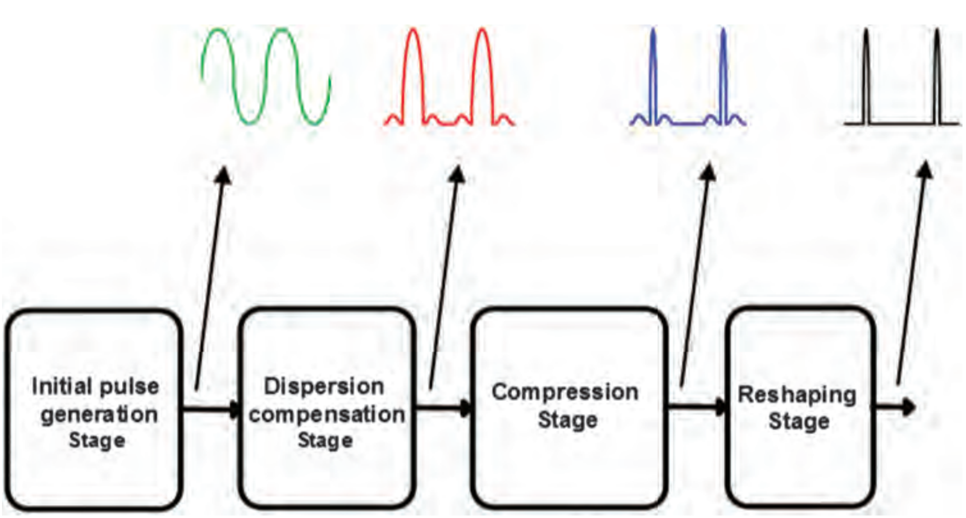

Fig. 2. General pulse source design.

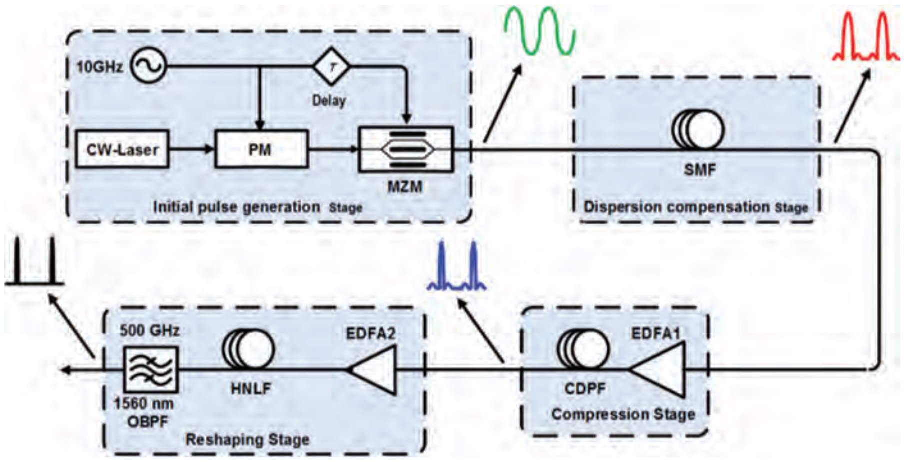

Fig. 3. Architecture of 10 GHz pulse source design and pulse intensity profiles.

source is shown in Figure 3. In the initial pulse generation (IPG) stage the PM ($V_\pi = 3.5$ V and modulation index $= 1.2\pi$) inserts a cyclic frequency chirp into the input CW beam at 1540 nm with 7.5 dBm power, including both negative and positive chirp. The MZM ($V_\pi = 5.5$ V and modulation index $= \pi$) carves the input beam into a sinusoidal form, both PM and MZM are driven by a 10 GHz sinusoidal signal as illustrated in Figure 3.

A variable electrical delay, τ, between the two modulators lets the synchronization of the phase and intensity modulations to select the sign of chirp in various parts of the beam. In this configuration, the optical pulse parts with optical intensity $I < I_{max}/2$ is aligned with the $-$ve chirp, while $I > I_{max}/2$ is aligned with the $+$ve chirp.[7,10] In the DC stage, a 7.5 km SMF ($D = 14$ ps/nm/km) is applied to compensate the $-$ve chirp,[7] and the pulse train is formed. Figure 4 represents theoretically the output of IPG stage with chirp and the output of DC stage.

This is followed by a pulse compression stage which is soliton based and consists of an EDFA1 (15 dB gain) and a CDPF as presented in Figure 3. A CDPF is a fiber span assembled by several alternating lengths of low and high-dispersion segments that aim to an effective pulse

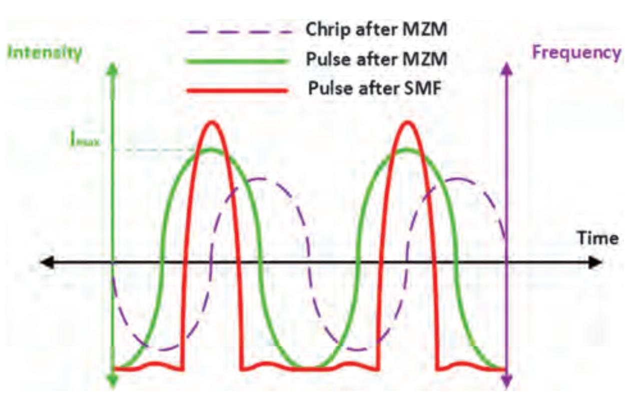

Fig. 4. The output of IPG stage (green) with chirp (violet dashed line) and the output of DC stage (red).

compression.[5,11] In the present fifteen parts are chosen of arranged SMF ($D = 14$ ps/nm/km) as high-dispersion segments and dispersion shifted fiber (DSF) as low-dispersion segments with total length 2.64 km. The CDPF functionality and imperfections will be tested and evaluated in Section 4. Finally, the pulse reshaping stage that targets reducing imperfections of the previous stage is applied.[5,7] This stage utilizes SPM with an EDFA2 (10 dB gain) and a 580 m HNLF ($D = -0.45$ $\text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$, $S = 0.0056$ $\text{ps/nm}^{-2}\cdot\text{km}^{-1}$ at 1550 nm, $\gamma \sim 10$ $\text{W}^{-1}\cdot\text{km}^{-1}$). This is followed by an offset Gaussian OBPF with 500 GHz bandwidth at 1550 nm.

3. RESULTS AND DISCUSSION

In this section, the system of the proposed pulse source is tested and evaluated through a trace and discussion for different key stages. Figure 5(a) represents the output of MZM (IPG stage) associated with the chirp resulting from PM. Figure 5(b) represents the signal after the DC stage as indicated in Section 3. After this stage, the pulse width is decreased to 13 ps.

Figure 6 displays the signal after processing through fifteen segments of CDPF in the pulse compression stage. The signal is compressed to ~3 ps. At the same time, it is found that there is a pulse pedestal in the optical time domain visualizer (OTDV) trace. The pedestal occurs because the CDPF has an excessive compression ratio, slightly deviating from the adiabatic soliton compression regime. The optical power injected into the CDPF is 12 dBm.

Figure 7, simulation results of single-pulse waveforms in different stages are depicted together for comparison. A significant width compression and pedestal suppression can be realized after the pulse reshaping stage. The pulse width after reshaping is reduced to 0.95 ps.

For exploring the behavior of the designed pulse source, the output from reshaping stage is multiplexed through an OTDM multiplexer. Figure 8(a) shows a high quality eye

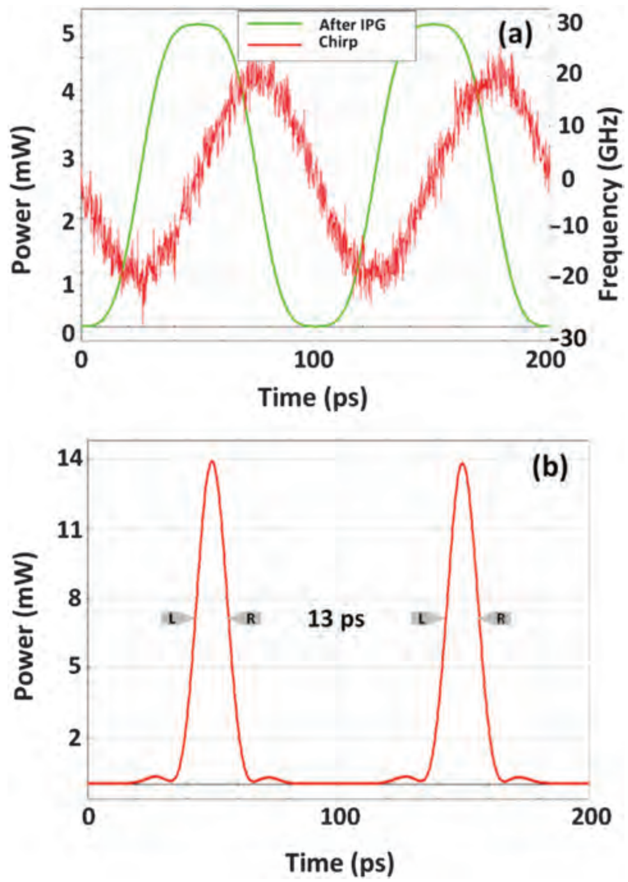

Fig. 5. (a) Signal after the IPG stage and the chirp, (b) Signal after the DC stage.

diagram of the 320 Gb/s OTDM. A clear eye opening and even channel spacing are observed. A negligible amplitude variation is observed indicating an optimized OTDM multiplexer operation. Figure 8(b) shows the output of OTDV for the multiplexed signal.

One advantage of using offset filtering its ability to improve the pulse ER during reshaping stage, as shown in Figure 9. In the simulation the input pulse has a 15 dB pulse extinction ratio. The pulse extinction ratio is

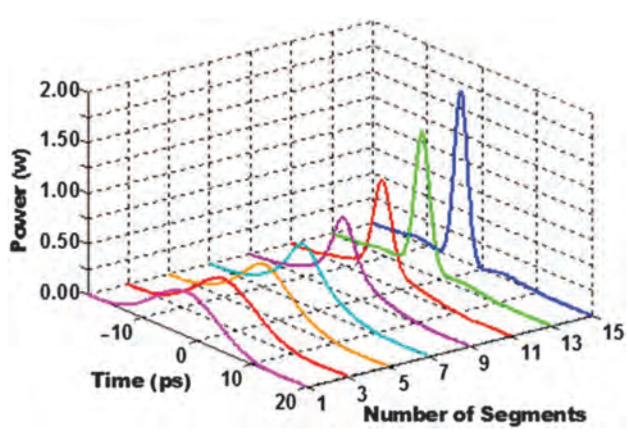

Fig. 6. Signal in the compression stage under soliton effect.

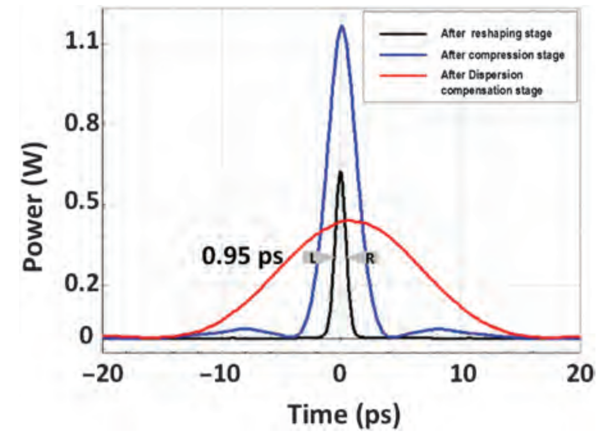

Fig. 7. Signal: after DC stage (red), after compression stage (blue), after reshaping stage (black).

improved by more than 66 dB during reshaping stage, in Figure 9 shown also the output ER after center filtering. This is understood by the following analysis: the SPM-induced chirp over pulse background is almost negligible

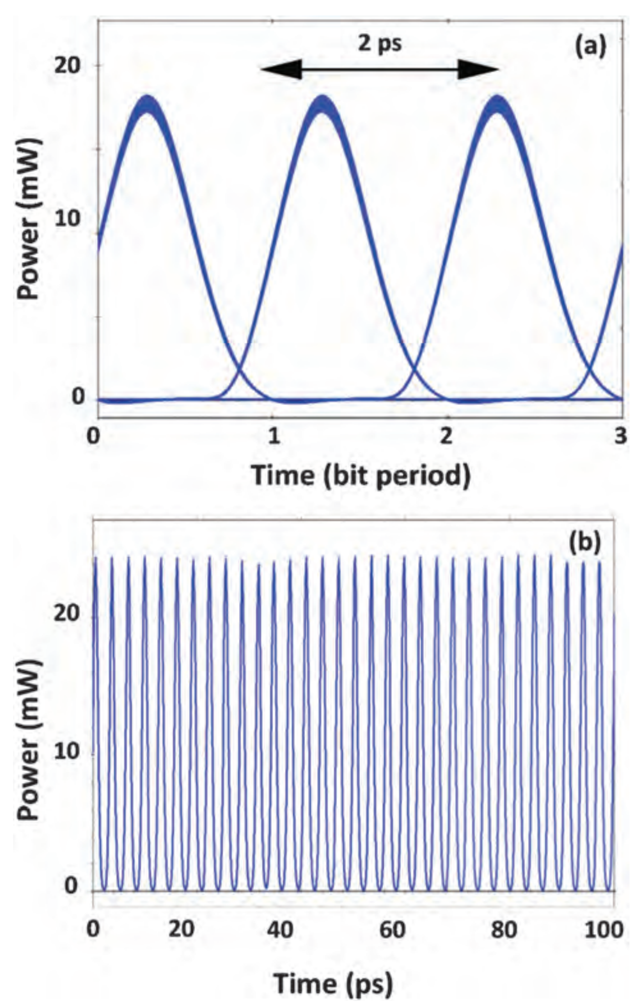

Fig. 8. (a) Eye diagram of the 320 Gbps OTDM signal. (b) The output of OTDV for the multiplexed signal.

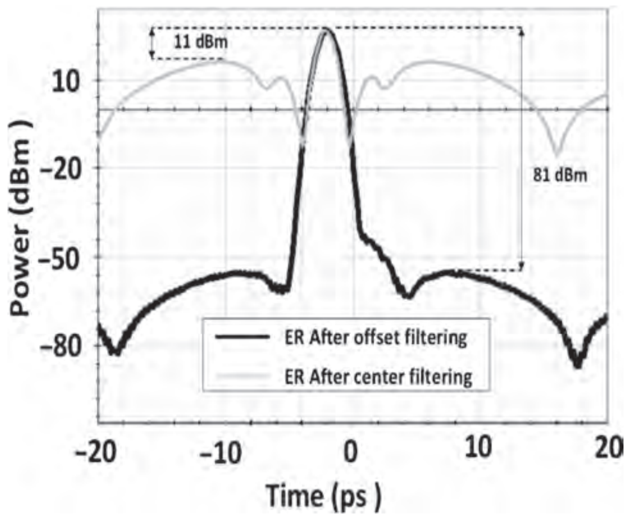

Fig. 9. ER after offset filtering (black), ER after center filtering (gray).

so under offset filtering the background level can be reduced greatly and thus the pulse extinction ratio can be improved.

This work also yields a very low timing jitter of 72 fs, as depicted from Figure 10. This value is the lowest one when compared with the related work as indicated in Section 5.

In practice, a pulse source with the feature of being wavelength tunable is desirable. Therefore, we characterize the pulse source for different wavelengths, by changing the wavelength of the tunable CW source and each time readjusting the filters. As shown in Figure 11(a), using a tunable Gaussian filter with a bandwidth of 500 GHz at the output of the pulse source, a consistent performance is obtained with 0.95 ps full width at half maximum (FWHM) at 1546.7, 1551.7, 1556.7 and 1561.7 nm. In addition, by adjusting the bandwidth of the Gaussian filter (500 GHz, 750 GHz, 1 THz and 1.25 THz), Gaussian pulses with different FWHM (950, 900, 850 and 800 fs) are obtained at 1546.7 nm as depicted in Figure 11(b).

A minimum time bandwidth product (TBP) of 0.475 is achieved for the designed pulse source at a Gaussian filter bandwidth of 500 GHz. The transform limited of the

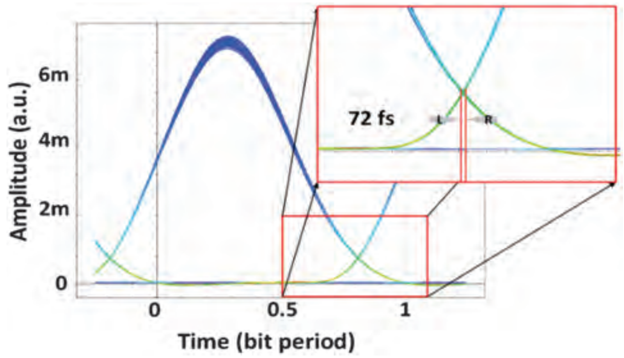

Fig. 10. Timing jitter and eye diagram.

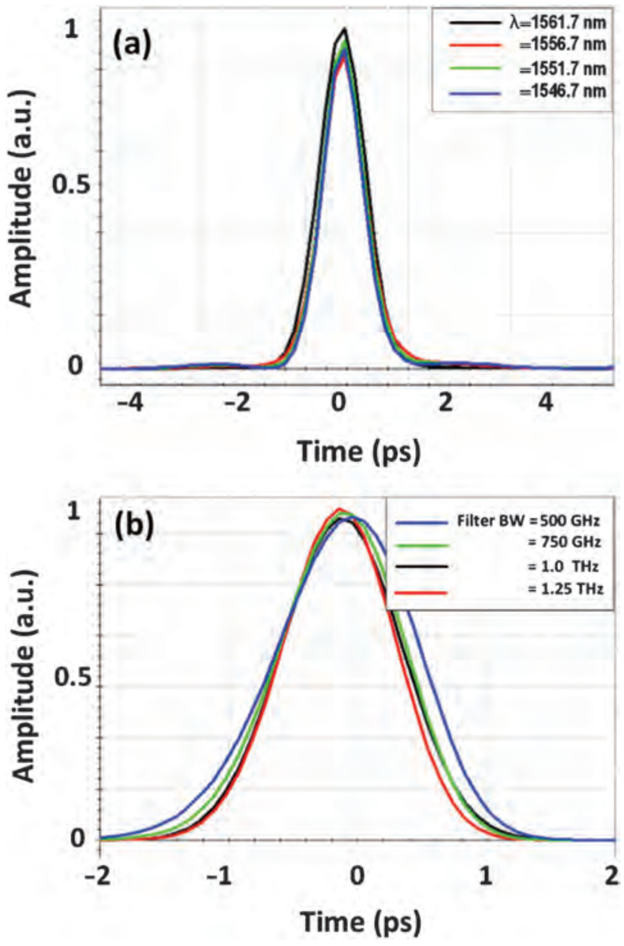

Fig. 11. Autocorrelation traces of the 10 GHz data pulse. (a) At different wavelengths. (b) At different 3-dB filter bandwidths.

TBP (0.441 for Gaussian pulses[3]) is not achieved because nonlinear chirp is generated at the edge of the broadened spectrum at the HNLF output that cannot be compensated by the dispersive elements. The TBP increases with the filter bandwidth since more uncompensated nonlinear chirp passes the filter when the bandwidth of the filter is larger. For bandwidth of the Gaussian filter (500 GHz, 750 GHz, 1 THz and 1.25 THz) the TBP is extracted by multiplying FWHM by the bandwidth of Gaussian OBPF to be 0.475, 0.675, 0.850, and 1.00, respectively.

4. COMPARISON WITH RELATED WORK

This section demonstrates an insight view for literature in Section 1 and related work that utilizes DCF/SMF in DC stage, soliton/SPM in compression stage and SPM in reshaping stage that are considered the key stages for an effective design of OTDM pulse source.[7] Table I presents detailed information about IPG stage, specifications of the DC stage, compression stage, and reshaping stage and performance evaluation indicators.

First, the IPG stage provides information about the type and specifications of the light source, and type of

Table I. Comparison with related work.

Author / Year	IPG stage: Light source and modulator	IPG stage: Wavelength (nm)	DC stage: Fiber type	DC stage: Fiber length (km)	Compression stage: Mo. stages	Compression stage: Fiber length (km)	Compression stage: Nonlinear tech.	Reshaping stage: HNLF length	Reshaping stage: Nonlinear
Y. Yang 2007 [5]	DFB-LD and EAM	1544.47	DCF	NA	One stage	5 DSF and 4.24 CDPF	Soliton-Effect	1	SPM
H. Hu 2007 [6]	DFB-LD and PM	1554	DCF	0.147	One stage	3.2	DSF Soliton-Effect	NA	NA
A. Wiberg 2009 [12]	ECL + MZM	1562	NA	NA	Two stages	0.3 HNLF and 0.1 HNLF	SPM	NA	NA
Q. Wang 2011 [10]	DFB-LD + PM	NA	SMF	1	NA	NA	NA	1	SPM
J. Chen 2011 [7]	DFB-CW and PM + MZM	1543.4	DCF	1	One stage	4.24 CDPF	Soliton-Effect	1	SPM
H. Hu 2011 [3]	CW-light and PM + MZM	1550	DCF	0.4	Two stages	1.4 HNLF and 0.8 HNLF	SPM	NA	NA
This work	CW laser and PM + MZM	1540	SMF	7.5	One stage	2.65 CDPF	Soliton-Effect	0.58	SPM

Table I. Continued.

Author / Year	Performance evaluation indicators: Pulse width (km)	Timing jitter tech.	Extinction ratio (ps)	Tunability (fs)	Stability (dB)	TBP	Stricture complexity
Y. Yang 2007[5]	1.1	NA	30	NA	Unstable	0.41	Medium complex structure
H. Hu 2007[6]	1.6	84	NA	NA	Stable	NA	Medium complex structure
A. Wiberg 2009 [12]	1.2	NA	20	NA	NA	NA	Medium complex structure
Q. Wang 2011[10]	1.33	113	25.1	NA	Stable	NA	Simple structure
J. Chen 2011[7]	1.38	132	NA	NA	Stable	NA	Simple structure
H. Hu 2011[3]	0.68	NA	NA	1535 nm∼1560 nm	Stable	0.485	Complex structure
This Work	0.95	72	81	1546 nm∼1561 nm	Stable	0.475	Simple structure

modulator. Type and fiber length characterizes the DC stage. Fiber length and nonlinearity technique are mentioned to identify compression stage and number of stages. HNLF length and type of nonlinearity are presented to define the reshaping stage. These specifications provide a reasonable view for the complexity of the related design techniques that are used to demonstrate a successful OTDM pulse source. Finally, performance evaluation previously mentioned indicators are introduced.

Table I indicates that the present work provides a remarkable pulse width of 0.95 ps with simple design and relatively low price components. This simple design takes place in utilizing one compression stage with lowest CDPF length and utilizing lowest HNLF length in the reshaping stage. Relatively low price arises when using SMF in the DC stage. The lower pulse width of 0.680 ps[3] is realized on the price of more stages and longer fiber lengths.

As indicated in Section 4, this work shares the stability property with literature that uses MZM/PM in IPG stage and soliton in pulse compression stage as in Chen et al.[7] For these stable operation designs,[3,7] there is no indication for the values of ER while it is calculated here to be 15 dB which is fairly accepted for OTDM pulse source specification. Also, Table I ensures a remarkable timing jitter among related work and an acceptable tunable range.

5. CONCLUSION

This work presents a simple and accurate design for a stable 10 GHz pulse generation scheme for 320 Gbps OTDM systems. Specifications for OTDM requirements are evaluated and achieved. The simplicity issue is addressed and compared to related literature. Operation stability and tunability over a wide range of wavelengths (1546–1561 nm) is achieved. A 0.95 ps Gaussian pulse with a negligible pedestal at wavelengths of concern is realized.

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