Width and Wavelength-Tunable Optical RZ Pulse Generation and RZ-to-NRZ Format Conversion at 10 GHz Using Spectral Line-by-Line Control

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***Abstract*—We demonstrate a method for tunable optical return-to-zero (RZ) pulse generation with large tunable wavelength range (1532∼1562 nm) and pulsewidth range (∼3–50 ps) at 10 GHz based on spectral line-by-line pulse shaping of a wavelength-tunable mode-locked laser. All-optical RZ-to-nonreturn-to-zero format conversion is also demonstrated.**

***Index Terms*—Format conversion, line-by-line pulse shaping, mode-locked laser, nonreturn-to-zero (NRZ), optical fiber communication, return-to-zero (RZ).**

RETURN-TO-ZERO (RZ) pulses have been widely used in optical fiber communication systems and optical networks, including RZ format transmission, soliton systems, optical time-division multiplexing, optical code-division multiple access, and optical packet generation. For example, RZ formats rather than nonreturn-to-zero (NRZ) formats have been applied in long-haul fiber transmission systems to extend transmission distance due to a possible higher tolerance to many fiber transmission impairments [1], [2]. As a result, the characteristics of RZ pulses in such systems play a critical role in optimizing system performance. Therefore, tunable RZ pulse generation is highly desirable in system contexts. Tunable width RZ pulses have been demonstrated based on various techniques [2]–[5]. The techniques in [2] and [3] require electrical modulation which is difficult at high bit rates and/or shorter pulses. Optical tunable width RZ pulse generation has also been demonstrated [4], [5], but relies on a relatively complicated nonlinear optical processing scheme with higher optical power requirement and lower efficiency, and/or limited width/wavelength-tunable range. In this letter, we demonstrate for the first time to our knowledge a linear optical technique for tunable RZ pulse generation with large tunable wavelength range (1532∼1562 nm) and pulsewidth range (∼3–50 ps) at 10-GHz repetition rate based on spectral line-by-line pulse shaping of a mode-locked laser. All-optical RZ-to-NRZ format conversion is also demonstrated using this method, which is desirable in optical networks where spectral efficiency is more important than transmission distance since the NRZ format is more spectrally efficient.

In the frequency domain, mode-locked laser pulses are characterized by a series of discrete spectral lines (optical frequency comb) with the frequency interval equal to the longitudinal mode spacing of the laser, or equivalently to the pulse repetition rate. The pulsewidth is proportional to the inverse of the spectral bandwidth, or roughly speaking, the number of spectral lines. From the pulse shaping perspective [6], essentially full pulse shape control can be achieved if it is possible to independently manipulate individual spectral lines. Specifically, the wavelength and width of the pulses can be tuned within the envelope of the input spectrum. Further, spectral line-by-line pulse shaping has very recently been demonstrated in a grating-based pulse shaper [7]. In this letter, we use this apparatus for tunable optical RZ pulse generation.

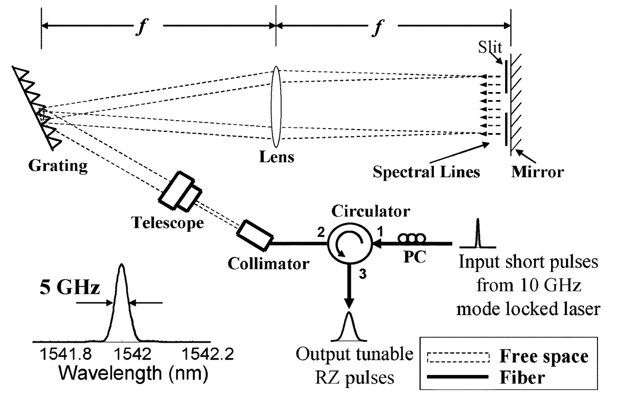

Fig. 1. Experimental setup of the line-by-line pulse shaper. PC: polarization controller. The inset figure shows the 5-GHz 3-dB passband of the pulse shaper.

Spectral line-by-line pulse shaping is implemented by the well developed ultrashort pulse shaping techniques [6] using a fiber coupled Fourier-transform pulse shaper. In order to achieve line-by-line pulse shaping, great care is taken in the pulse shaper design to improve resolution. Fig. 1 shows the line-by-line pulse shaper experimental setup. A fiber coupled pulse shaper with a reflective geometry is built, which includes a collimator and telescope combination to produce a collimated beam with ∼18-mm diameter, an 1100-grooves/mm grating, a lens with 750-mm focal length, a retro-reflecting mirror, and a circulator. Here, we use a tunable slit to achieve the required line-by-line control for RZ pulse generation. In this experiment, the line-by-line pulse shaper functions as a wavelength and bandwidth tunable high resolution optical filter for precise spectral line-by-line control. Using a broad-band source, the measured passband of the line-by-line pulse shaper has a minimum 5-GHz 3-dB passband width, as shown in the inset figure. To the best of our knowledge, this is the highest

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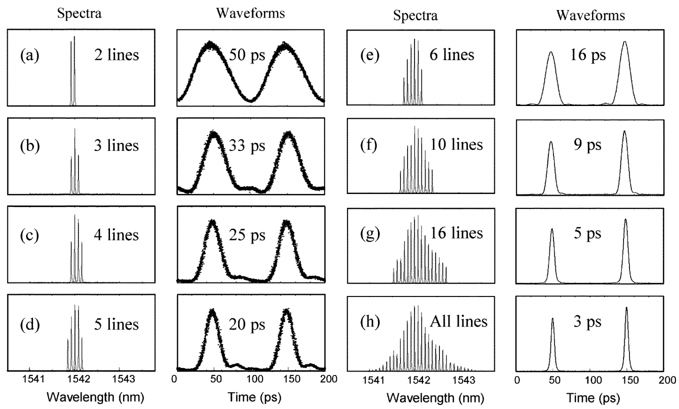

Fig. 2. Line-by-line controlled spectra (linear scale) and waveforms, where the laser center wavelength is tuned to 1542 nm. The spectra are controlled to have (a) two lines, (b) three lines, (c) four lines, and (d) five lines. These waveforms are detected by a 50-GHz photodiode and sampling scope, showing tunable width of 50, 33, 25, and 20 ps, respectively. The spectra are controlled to have (e) six lines, (f) ten lines, (g) 16 lines, and (h) all lines. These waveforms are measured by intensity cross-correlation measurements, showing tunable width of 16, 9, 5, and 3 ps after deconvolution, respectively.

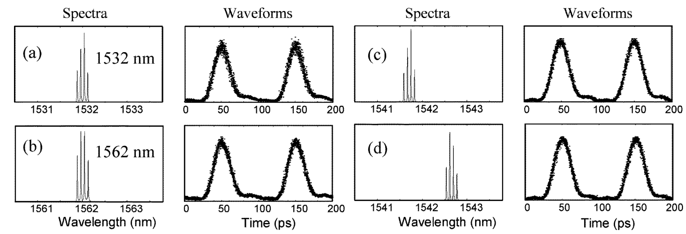

Fig. 3. Line-by-line controlled spectra (linear scale) and waveforms, where four lines are transmitted through the line-by-line pulse shaper to generate 25-ps width pulses. Center wavelength is tuned to (a) 1532 and (b) 1562 nm by tuning both the mode-locked laser center wavelength and coarsely tuning the pulse shaper (the grating angle). Center wavelength is finely tuned around 1542 nm (c) and (d), by tuning the pulse shaper alone (translation of slit).

resolution ever reported for a grating-based pulse shaper. Note that our line-by-line pulse shaper is finely adjusted to achieve zero-dispersion [6], which is confirmed by negligible broadening for 400-fs pulses passing through the pulse shaper without spectral filtering. Therefore, the added chirp on the generated RZ pulses is negligible. On the other hand, chirped RZ pulses are also useful for fiber transmission experiments to optimize system performance [1]. The pulse shaper can also be designed to generate RZ pulses with tailored chirp [6].

Our experiments are performed using a home-made harmonically mode-locked fiber laser producing $\sim$3-ps [full-width at half-maximum (FWHM)] pulses at 10 GHz with center wavelength that can be tuned from 1532 to 1562 nm as input to the pulse shaper. Fig. 2 shows the shaped spectra and corresponding waveforms, where the laser center wavelength is tuned to 1542 nm. The number of spectral lines is controlled by the slit width in the line-by-line pulse shaper. The waveforms in Fig. 2(a)–(d) are detected by a 50-GHz photodiode and sampling scope after an optical amplifier. Fig. 2(a) shows two spectral lines separated by the 10-GHz laser repetition rate. The optical linewidths are limited by the 0.01-nm resolution of the optical spectrum analyzer used for this measurement. Other spectral lines are well blocked [higher than 25-dB suppression ratio in Fig. 2(a)] due to the high resolution line-by-line shaper. Since there are only two spectral lines, ideally the waveform intensity profile in the time domain corresponds to a cosine function (with a dc offset). The waveform in Fig. 2(a) indeed shows a cosine function with 50-ps width (FWHM). Fig. 2(b)–(d) show three, four, and five spectral lines transmitted through the line-by-line pulse shaper. Accordingly, the generated RZ pulses exhibit 33-, 25-, and 20-ps widths, respectively, which clearly illustrates that tunable width optical RZ pulses have been produced. Since the waveform measurement is limited by the 50-GHz bandwidth photodiode and sampling scope, for generated pulses shorter than 20 ps, we measure them by standard short pulse intensity cross-correlation measurement, where the unshaped 3-ps pulse is used as the reference. Fig. 2(e)–(h) show six, ten, 16, and all spectral lines transmitted by the line-by-line pulse shaper, respectively. Accordingly, the generated RZ pulses are tuned from 16 to 3 ps (after deconvolution). The two pulses measured within each trace have different peak values due to nonperfect-alignment of the cross-correlation measurement apparatus. Fig. 2 demonstrates the width tunability of our method in a range of 3–50 ps. Assuming the optical bandwidth is (number of spectral lines $-1) \times 10$ GHz, the time-bandwidth product of the generated pulses is in the range of 0.5$\sim$0.81 in Fig. 2(a)–(g). This is intermediate between that expected for transform-limited Sech pulses (0.315) and for transform-limited pulses with rectangular spectrum (0.88). This is reasonable due to the rectangular-like truncation of the power spectra in our current experiments. For the source limited 3-ps pulses, the 3-dB time-bandwidth product is approximately 0.33, close to transform limit for Sech pulses. This also confirms that chirp due to the pulse shaper is negligible.

Fig. 3 shows the generated pulses for different center wavelengths. Tunability over broad wavelength range can be accomplished by tuning both the mode-locked laser center wavelength and coarsely tuning the pulse shaper (the grating angle), as show in Fig. 3(a) and (b), where four spectral lines are transmitted by the line-by-line pulse shaper to generate 25-ps pulses at 1532 and 1562 nm, showing 30-nm wavelength tuning range. For finely tuning the wavelength within the bandwidth of the mode-locked laser, one can tune the pulse shaper alone (translation of slit), as shown in Fig. 3(c) and (d), where 25-ps pulses are generated with different center wavelengths around 1542 nm. Note that the tuning range via the pulse shaper alone is limited to the available bandwidth of the mode-locked laser. This limitation can be relaxed or eliminated by utilizing short pulse compression techniques to achieve large bandwidth at high repetition rate [8].

Finally, we use the line-by-line pulse shaping technique to achieve all-optical RZ-to-NRZ format conversion. Although the RZ format has been widely employed in long-haul fiber transmission systems as it has a higher tolerance for important impairments caused by fiber transmission effects, the NRZ format is more spectrally efficient and can be used in local and metro access networks where spectral efficiency is important. Therefore, all-optical RZ-to-NRZ format conversion is desirable at the interface between backbone and access networks. This conversion can be realized by various techniques, for example, based on relatively complicated nonlinear optical processing using semiconductor optical amplifier-based devices [9], [10], or cross-phase modulation in dispersion-shifted fiber [11]. Here we use

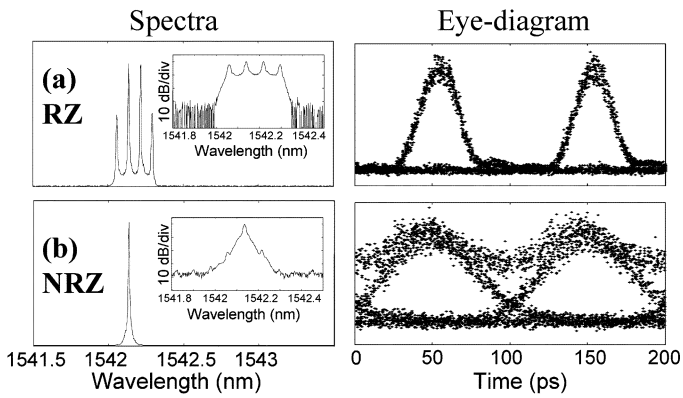

Fig. 4. RZ-to-NRZ format conversion by line-by-line pulse shaping. Spectra and eye diagrams for (a) data modulated RZ format with four spectral lines, (b) converted NRZ format with only one spectral line. Inset figures show the spectra in log scale.

line-by-line control, a linear technique, to achieve all-optical RZ-to-NRZ format conversion.

The generated RZ pulses are modulated and become an RZ format data stream. Fig. 4(a) shows RZ format pulses modulated by a 10-Gb/s pseudorandom binary sequence $2^{23}-1$ data stream with four spectral lines (25-ps pulses) transmitted by the line-by-line pulse shaper. Compared with the unmodulated spectra shown in Fig. 2, in 3, each spectral line of the modulated spectra is broadened by the data modulation as shown in the figure. Here the line-by-line shaper is placed after the data modulator for experimental convenience. The modulated waveforms are detected by a 50-GHz photodiode in which the RZ format is clear. In Fig. 4(b), only one spectral line is allowed to pass the line-by-line pulse shaper. As a result, the RZ format is converted to NRZ format, as shown by the eye diagram also detected by the 50-GHz photodiode. Higher spectral efficiency is clear for NRZ since it occupies less bandwidth with one spectral line rather than the bandwidth for RZ with multiple lines. The nonideal converted NRZ format (uneven "1" level) is caused by imperfect suppression of adjacent spectral lines (~20-dB suppression ratio) as shown by the log-scale optical power spectra in the figure insets. The "1" level can be made more flat by narrowing the pulse shaper filter bandwidth to suppress undesired lines more completely, but the eye diagram becomes noisy and performance degrades. The increased noise is caused by optical frequency fluctuations in the mode-locked laser comb. Filtering to one single line (NRZ format) has the highest sensitivity to such fluctuation while filtering to produce multiple spectral lines (RZ format) has better tolerance, as evidenced by different noise levels in the eye diagrams. The laser used in our system is relatively stable at 10-GHz mode-locking frequency (around 0.01-nm optical frequency fluctuations) making line-by-line pulse shaping and the current experiments possible in typical experimental environment conditions without additional control (for example, without temperature stabilization). The performance of the generated 25-ps RZ format and converted NRZ format are further confirmed by bit-error-rate measurement (not shown). For both formats, less than 10^{-10} bit-error rate can be achieved using a standard 10-Gb/s receiver for both back-to-back and after 25-km single-mode fiber transmission without dispersion compensation. The line-by-line pulse shaping performance is expected to be improved with an optical-frequency-stabilized mode-locked laser [12]. In our experiment, only a single line-by-line pulse shaper is used to emulate the RZ-to-NRZ format conversion. In practice, one line-by-line pulse shaper can be used to generate the RZ format with desired wavelength and width while utilizing another line-by-line pulse shaper to implement RZ-to-NRZ format conversion.

In the current experiment, the width of the RZ pulses is discretely tunable by simply changing the number of spectral lines. The pulsewidth can be continuously tuned by controlling not only the number of lines but also the relative amplitudes of the selected lines using a programmable amplitude line-by-line pulse shaper [7].

In conclusion, we have demonstrated for the first time to our knowledge tunable optical RZ pulse generation without additional chirp based on spectral line-by-line pulse shaping of a wavelength-tunable mode-locked laser. Up to 30-nm wavelength tuning range (1532–1562 nm) and ~3–50-ps pulsewidth range at 10-GHz repetition rate have been achieved. RZ-to-NRZ format conversion is also demonstrated using this technique without the need for any external pulse duplicator. This method can readily be applied to higher repetition rates for tunable RZ pulse generation and RZ-to-NRZ format conversion, for example, at 40 GHz.

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