논문번호 06-02-01

Arbitrary Waveform Generation via Spectral Line-by-Line Pulse Shaping on Mode-Locked Pulses

Dong Sun Seo*, Zhi Jiang**, and Andrew M. Weiner**

Abstract

We have built a grating-based, high-resolution, spectral line-by-line pulse shaper. By controlling individual spectral lines of a mode-locked laser output, we demonstrate the interesting functionalities of the pulse shaper for arbitrary waveform generation, such as width tunable pulse generation, phase controlled waveform generation, microwave waveform generation, etc.

Keywords : Pulse Shaping, Arbitrary Waveform Generation, Width Tunable Pulse Generation, Microwave Waveform Generation

I. Introduction

The Fourier transform pulse shaper is an important tool for controlling the waveforms (both temporal intensity and phase) of mode-locked ultrashort optical pulses [1]. 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 frequency repetition rate. From the pulse shaping prospective, if it is possible to independently manipulate both amplitude and phase of individual spectral lines, essentially full pulse shape control can be achieved. However, in typical pulse shapers spectral lines are manipulated in groups rather than individually. This is primarily due to the practical difficulty of building a pulse shaper capable of resolving each spectral line for typical mode-locked laser with repetition rates below several GHz. Here we use a high resolution spectral line pulse shaper capable to manipulate individual lines as well as groups.

In group-of-line pulse shaping, where shaping occurs M lines at a time, the shaped pulses have maximum duration ~ 1/(M*frep) and repeat with the period T = 1/frep (the inverse of the pulse repetition rate). Accordingly the shaped pulses are isolated in time, which may be favorable when the pulse overlap is not desirable. One interesting application of this group-of-line shaping is in optical code division multiple access (O-CDMA) communications and networking, in which multiple users share a fiber optic channel on the basis of different waveforms (codes) assigned to different data channels [2]. For individual spectral line shaping, in contrast with above group shaping, the shaped pulses can overlapped with each other which leads to interference between contributions from different input pulses in the overlapped region. For example, if we simply select two of spectral lines, a sinusoidal waveform can be observed all the time. This means that we can generate an arbitrary waveform by deliberate controlling of individual spectral lines [3].

---

* Dept. of Electronics and MITERI, MyongJi University.
** School of Electrical and Computer Engineering, Purdue University, USA.
※ This work was supported by Inha University ERC (OPERA).
Manuscript received Jul. 15, 2006; accepted Oct. 13, 2006.

In this paper, we report a high-resolution grating-based pulse shaper that is able to manipulate individual spectral lines from an actively mode-locked fiber laser of which repetition rates can be tuned between 8 GHz and 13 GHz.The repetition rate is selected to ensure that the spectral line spacing exceeds the pulse shaper resolution. By performing amplitude and phase line-by-line pulse shaping, we generate arbitrary waveforms; width tunable pulses, phase-controlled waveforms, and microwave waveforms, etc.

II. Experimental Set-up

Fig. 1 shows a spectral line-by-line pulse shaper used in the experiment, which has better resolution than that used in our former results [3]. A fiber coupled Fourier-transform pulse shaper is constructed in a reflective geometry. A fiber pigtailed collimator and subsequent telescope take the light out of fiber and magnify the beam size to ~18 mm diameter on a 1200 grooves/mm grating in order to enhance the pulse shaper resolution. Discrete spectral lines making up the input short pulse are diffracted by the grating and focused by the lens with 1 m focal length. A fiberized polarization controller (PC) is used to adjust for horizontal polarization on the grating. A 2 x 128 pixel liquid crystal modulator (LCM) array is placed just before the focal plane to independently control both amplitude and phase of each spectral line. The individual pixels of the LCM, arranged on 100 um centers, can be electronically controlled to give an amplitude modulation and a phase shift in the range of 0 to 2π with 12-bit resolution. A retro-reflecting mirror leads a double-pass geometry, with all spectral lines recombined into a single fiber and separated the input via an optical circulator. The fiber coupled input-output loss of the pulse shaper is 11.6 dB (including the circulator loss), which includes all optical component losses as well as loss incurred in focusing back into the 9 um fiber mode after the pulse shaper. The measured resolution (bandwidth controlled by an individual LCM pixel) is 2.6 GHz at 3dB points. The high resolution makes accurate control of individual spectral lines possible and enables true line-by-line pulse shaping control, potentially over a broad optical band. In our experiments, otherwise not specified, temporal waveforms are detected by a 50 GHz phodo-detector coupled with a sampling scope, and optical spectra are measured an optical spectral analyzer with 0.01 nm resolution.

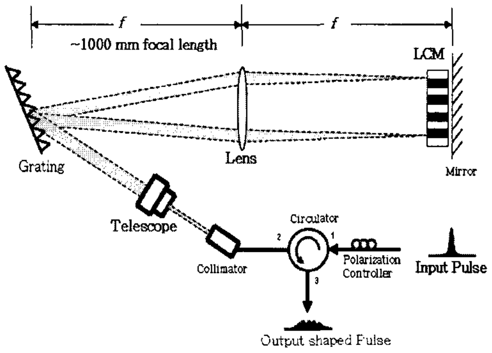


Figure 1. Experimental set-up for line-by-line pulse shaping

III. Width Tunable Optical Pulse Generation

Tunable width pulses are highly desirable in many optical fiber communication systems and networks, including RZ (return-to-zero) format transmission, soliton systems, optical time division multiplexing, optical code-division multiple access, and optical packet generation. Optical tunable width generation has been demonstrated [4,5], but relies on relatively complicated nonlinear optical processing scheme with higher optical power requirement and low efficiency, and/or limited bandwidth/wavelength tuning range. In the frequency domain, mode-locked laser pulses are characterized by a serious 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 pulse width is proportional to the inverse of the spectral width, or roughly speaking, the number of spectral lines. By manipulating individual spectral lines, we can tune the width as well as the wavelength of the pulses within the envelope of the input pulse spectrum. Fig. 2 shows the line-by-line controlled spectra and waveforms, where the laser center is tuned to 1542 nm. The number of spectral lines is controlled by passing desired lines at the LCM of the pulse shaper. Fig. 2(a) shows 2 spectral lines separated by the 10 GHz laser repetition rate. The optical line widths are limited by the 0.01 nm resolution of the spectral analyzer used for this experiment. Other spectral lines are well blocked due to the high resolution line-by-line shaper. Since there are only two of spectral lines, ideally the waveform intensity profile in the time domain corresponds to a cosine function. The waveform in Fig. 2(a) indeed shows a cosine function with 50 ps width (FWHM) at 10 GHz repetition rate. Fig 2(b)-(d) show 3, 4 and 5 spectral lines transmitted through the line-by-line pulse shaper. Accordingly, the generated pulses exhibit 33 ps, 25 ps and 20 ps widths respectively which clearly illustrate that tunable width optical pulses have been produced. Since the waveform measurement is limited by the 50 GHz bandwidth photo-diode and sampling scope, for generated pulses shorter than 20 ps, we measure them by standard short pulse intensity cross-correlation measurement, where the un-shaped 3 ps pulses is used as the reference. Fig 2(e)~(h) show 6, 10, 16 and all spectral lines transmitted by the line-by-line pulse shaper, respectively. Accordingly, the generated pulses are tuned from 16 ps to 3 ps (after deconvolution). The two pulses measured within each trace have different peak values due to non-perfect-alignment of the cross-correlation measurement apparatus. Fig. 2 demonstrates the width tunability of our method in a range of 3 ps to 50 ps. Assuming the optical bandwidth is (number of spectral lines -1) X 10 GHz, the time-bandwidth product of the generated pulses is in the range of 0.5~0.81 in Figs 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

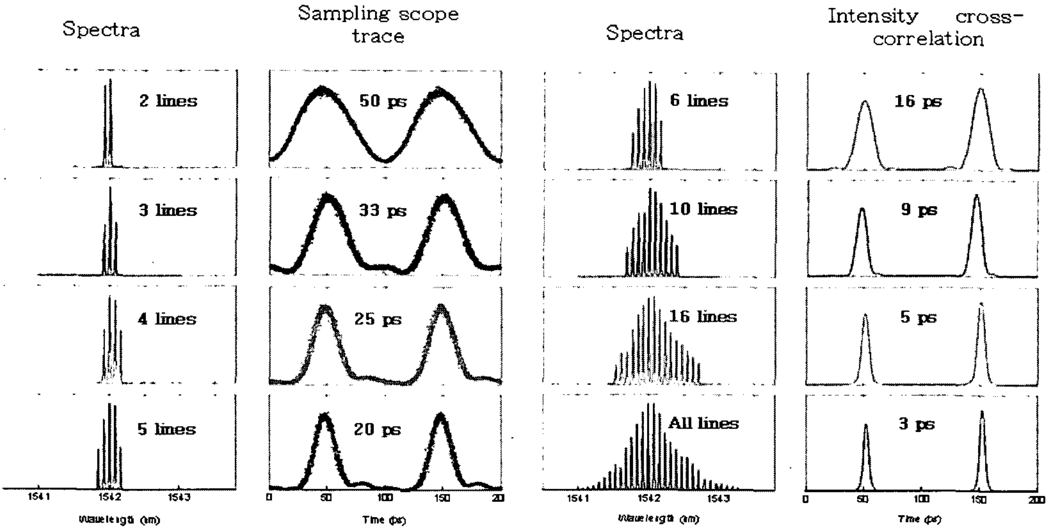


Fig. 2. Spectra and waveforms of width variable pulses generated by line-by-line spectral controlling. The spectra are controlled to have (a) 2 lines, (b) 3 lines, (c) 4 lines, (d) 5 lines, (e) 6 lines, (f) 10 lines, (g) 16 lines, and (h) all lines. The waveforms are detected by a 50 GHz sampling scope coupled with 50 GHz photodetector, showing tunable widths of (a) 50 ps, (b) 33 ps, (c) 25 ps, (d) 20 ps, respectively, and by a cross-correlation measurements, showing (e) 16 ps, (f) 9 ps, (g) 5 ps, and (h) 3 ps, respectively.

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.

IV. Phase Controlled Waveform Generation

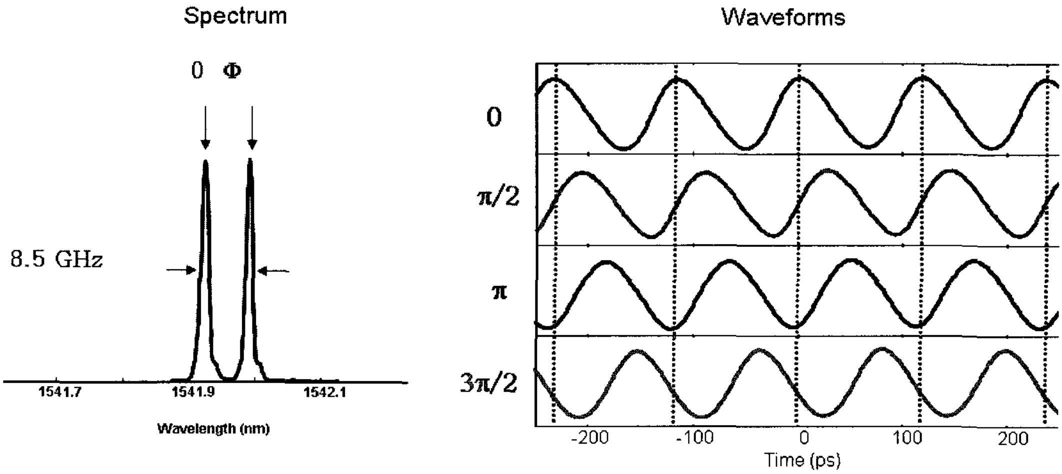


Fig. 3. Phase modulation of two spectral lines; (a) selected spectral lines and (b) sampling scope traces with phase shift (0, π/2, π, 3π/2) on the line.

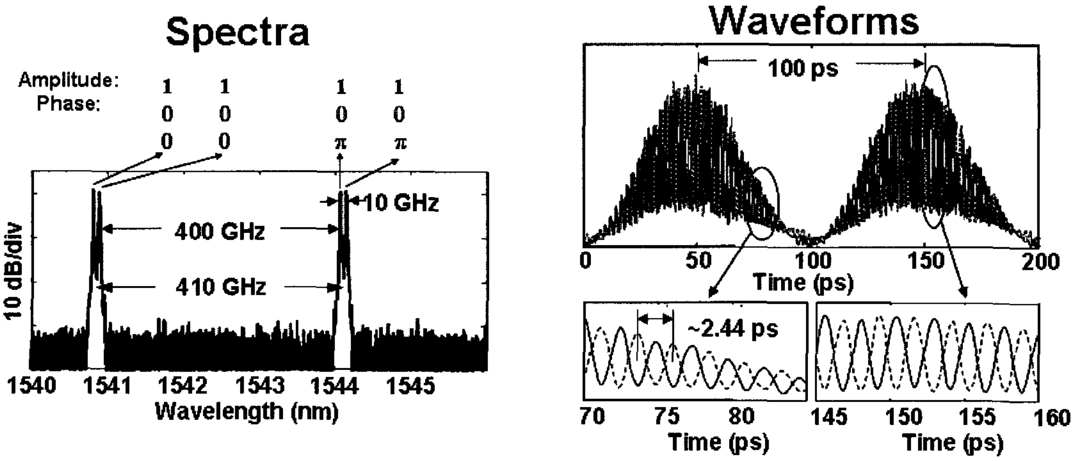


Fig.4. Phase modulation of four of spectral lines, in which two pairs of spectral lines are separated by 410 GHz and the two lines in each pair are separated by 10 GHz. The resulting waveforms have 100 ps (corresponding to 10 GHz) envelope period and 2.44 ps (corresponding to 410 GHz) carrier period. The solid and dotted lines are controlled to be out of phase by applying πphase shift on one pair of spectral lines, as shown in the zoomed figures.

Here we select two lines from a mode-locked output by blocking all other lines and control the phase of one of the selected spectral lines. To show the flexibility of our pulse shaper, we operated our mode-locked laser at 8.5 GHz. Fig. 3 shows the capability of line-by-line phase control by phase shifting one of two spectral lines. As we discussed before, the waveform intensity profile in the time domain corresponds to a cosine function in which the temporal phase of the cosine function is determined by the relative phase between the two spectral lines. Sampling scope traces with phase shift (0, π/2, π, 3π/2) on the line are shown in Fig. 3(b). As expected the waveforms also phase shifted corresponding to the amount of phase shift on the line.

In principle, any periodic waveform can be constructed from a complete set of harmonic (cosine and sine) waveforms. Fig 4 shows an example of line-by-line pulse shaping control by manipulating multiple spectral lines over a broad optical band. To form a broad band pulses with 6 nm spectral and 0.4 ps time widths, we use soliton pulse compression of the mode-locked output [6]. Two pairs of spectral lines are simultaneously selected and controlled, with 10 GHz frequency separation within each pair and 410 GHz center-to-center frequency separation between pairs (Fig 4(a)). The time domain waveform was measured by cross-correlation measurements between the shaper output and 0.4 ps reference input pulse. There is clear relationship between the spectral lines in the frequency domain and the waveform generated in the time domain: the 100 ps envelope period of the waveform is determined by the 10 GHz spacing between lines within a single pair, while the ~2.44 ps carrier period of waveform oscillation is determined by the average 410 GHz spacing between pairs (Fig 4(b)). To demonstrate fine scale waveform control, a π phase shift is applied to one

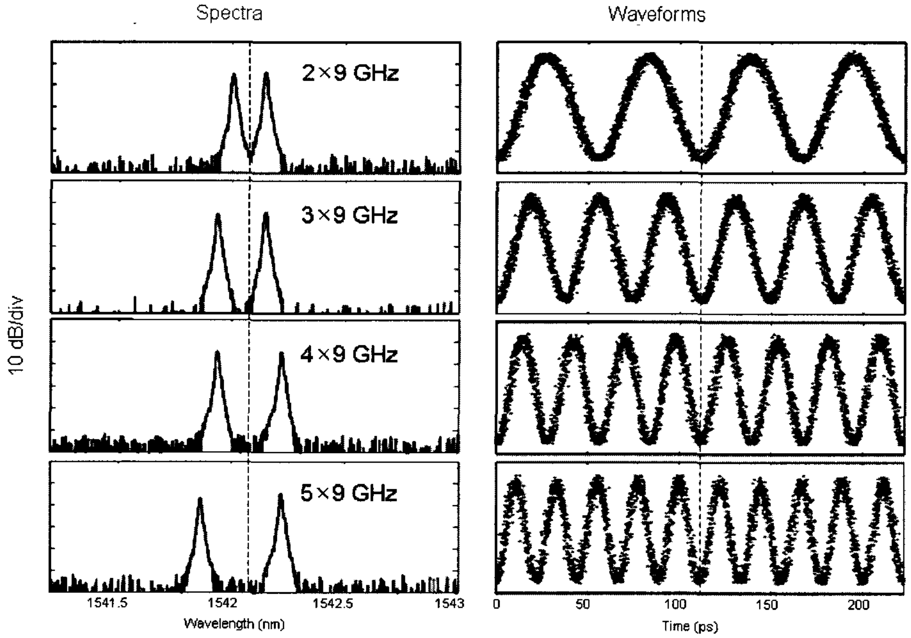


Fig. 5. Microwave waveform generation by beating signal between two selected lines (left: optical spectra, and right: waveforms). The separation between the spectral lines are (a) 9 Ghz, (b) 18 GHz, (c) 27 GHz, and (d) 36 GHz.

pair of spectral lines while keeping the spectral amplitude essentially unchanged. The resulting time domain waveform should be out of phase compared with the waveform without the phase shift, exactly as seen in the zoomed figures. The finite contrast of the waveform oscillation minimum points, which should go to zero theoretically, is explained by the finite duration of the 0.4 ps reference pulses used for the measurement. These examples demonstrate an unprecedented capability for true line-by-line pulse shaping control, with waveform manipulation at both envelope and carrier scale simultaneously.

Ⅴ. Microwave Waveform Generation

Now we select two lines with different separations to beat for microwave waveform synthesis, as shown in Fig. 5. The waveforms are generated after O/E conversion using a 50 GHz photo-diode, where 18 GHz, 27 GHz, 36 GHz and 45 GHz waveform are shown. The undesired spectral lines are well suppressed (higher than 34 dB suppression ratio, limited by the optical spectra measurements), making high purity microwave generation possible. Other frequencies and their harmonics can be readily generated by tuning the driving frequencies of the mode locked laser (from 8 GHz to 13 GHz in our case). Optically generated microwave signals have the potential to impact fields such as ultra-wideband (UWB) wireless communications, impulsive radar and radio-over-fiber.

Ⅵ. Conclusion

We have built a grating-based, high-resolution, spectral line-by-line pulse shaper which has a capability of controlling individual spectral lines of a mode-locked laser output. By individual spectral line shaping, we demonstrate arbitrary waveform generation from mode locked outputs. By manipulating individual spectral lines, we could determine the number of spectral lines around specific center wavelength, allowing width and wavelength tunable pulse generation. By controlling the phase of the selected spectral lines we could also generate phase controlled waveforms. In addition to that by selecting and beating two of spectral lines with different separation, we could achieve microwave waveform generation. The interesting functionalities of the high-resolution pulse shaper prove its potential for many applications in optical communications and microwave photonics.

References

[1] A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," *Rev. Sci. Instr.*, vol. 71, pp. 1929-1960, 2000.

[2] Z. Jiang, D. S. Seo, S.-D. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, "Four user, 2.5 Gb/s, spectrally coded O-CDMA system demonstration using low power nonlinear processing," J. Lightwave Technol., vol. 23, no. 1, pp. 143-158, Jan. 2005.

[3] Z. Jiang, D. S. Seo, D. E. Leaird, and A. M. Weiner, "Spectral line-by-line pulse shaping", Optics Lett., vol. 30, no. 12, pp. 1557-1559, Jun. 2005.

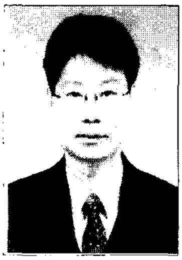
[4] M. Matsura, N. Kishi, and T. Miki, "Widely pulsewidth-tunable multiwavelength synchronized pulse generation utilizing a single SOA-based delay interferometric switch", *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 902-904, Mar. 2005.

[5] C. Yu, L.S. Yan, T. Luo, Y. Yang, Z. Pan, and A. E. Willner, "Width-tunable optical RZ pulse train generation based on four-wave mixing in highly nonlinear fiber", *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 636-638, Mar. 2005.

[6] D.S. Seo and A.M. Weiner, "Ultrashort Optical Pulse Generation at 10 GHz by Pulse Compression of Actively Mode-Locked Fiber Laser Output", *J. IKEEE*, vol. 9, no. 2, pp. 115-122, 2005. 12.

Biography

Dong Sun Seo (Member)



D. S. Seo received the B.S. and M.S. degrees in electronics *engineering from* Yonsei University, in 1980 and 1985, respectively, and Ph.D. degree in electrical engineering (optoelectronics) from the University of New Mexico, USA, in 1989. In 1990, he joined the faculty of Myongji University, where he is a Professor with the Department of Electronics. From 1994 to 1995, he was a Visiting Research Fellow at the Photonics Research Laboratory, University of Melbourne, Australia. From 2002 to 2004, he was a Visiting Research Professor with the School of Electrical and Computer Engineering, Purdue University, USA. His current research interests are in the areas of ultra short pulse technology, optical CDMA, microwave photonics, optical communications. and optical measurements.

Zhi Jiang (Member)

Z. Jiang received the B.S. and M.S. degrees in electronics engineering from Tsinghua University, China in 1999 and 2002, respectively, and Ph.D. degree in electrical engineering from Purdue University, USA, in 1996. He is currently a Postdoctoral Research Fellow at the School of Electrical and Computer Engineering, Purdue University, USA. His research focuses on the areas of pulse shaping, optical CDMA, optical fiber nonlinearity, and optical communications.

Andrew M. Weiner (Honored Member)

A. M. Weiner received the Sc.D. degree in electrical engineering from the Messachusetts Institute of Technology (MIT), USA, in 1984. In 1984, he joined Bellcore where he promoted to Manger of Ultrafast Optics and Optical Signal Processing, in 1989. He joined Purdue University, USA, in 1992, as a Professor of the School of Electrical and Computer Engineering. His research focuses on ultrafast optical signal processing and high speed optical communications.