

# Spectral Line-by-Line Pulse Shaping

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**Abstract:** We experimentally demonstrate spectral line-by-line pulse shaping. The shaped pulses overlap in time, which leads to observation of a new time-dependent noise process directly linked to variations in the comb-offset frequency.

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In the frequency domain, ultrashort laser pulses are characterized by a series of discrete spectral lines (optical frequency comb) with the frequency interval equal to the pulse repetition rate. Spectral lines and their stabilization in mode-locked lasers have recently played a critical role in the progress of optical frequency metrology and optical carrier-envelope phase control [1,2]. It has been shown that the optical spectral lines (optical frequency comb) for a mode-locked laser can be expressed as [1]

$$f_n = n\Delta f + e \quad (1)$$

where  $n$  is a large integer,  $\Delta f$  is frequency interval between two spectral lines (also the repetition rate of mode-locked laser), and  $e$  is the comb-offset frequency. The offset frequency  $e$  is related to the evolution of the carrier-envelope phase, which occurs as the result of a mismatch in the group and phase velocities inside the laser cavity. Therefore, stable (unstable) offset frequency  $e$  implies fixed (fluctuating) phase relationship between adjacent pulses. If the adjacent pulses can be manipulated in a way such that they overlap with each other, this phase relationship can be observed through their interference.

From the pulse shaping perspective [3], if it is possible to independently manipulate both the amplitude and phase of individual spectral lines, essentially full pulse shape control can be achieved. Specifically, adjacent pulses can overlap with each other. However, in typical pulse shapers [3] spectral lines are typically 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 lasers with repetition rates below 1 GHz. Group-of-lines pulse shaping is illustrated in Fig. 1(A), where  $\Delta f$  represents the spectral line spacing. Assuming that the pulse shaping occurs  $M$  lines at a time, the shaped pulses have maximum duration  $\sim 1/(M\Delta f)$  and repeat with period  $T=1/\Delta f$ . Accordingly, the pulses are isolated in time. In contrast, for line-by-line pulse shaping as shown in Fig. 1(B), the shaped pulses can overlap with each other, which leads to interference between contributions from different input pulses in the overlapped area. Previously, a hyperfine WDM filter was used for spectral line-by-line manipulation in an optical code division multi-access system [4], but without investigating this pulse overlapping issue. More seriously, this hyperfine WDM device has a periodic spectral response, which means that independent manipulation of the spectrum is possible only within one free spectral range, which was only 80 GHz in the experiments of [4]. In this paper, we report a high resolution grating based pulse shaper that is able to resolve individual spectral lines from an 8.5 GHz repetition rate actively mode-locked fiber laser. By performing amplitude and phase line-by-line pulse shaping experiments, we are able to generate waveforms in which shaped pulses arising from different input pulses clearly overlap. This leads to observation of a new time-dependent noise process, directly linked to variations in the comb-offset frequency.

Spectral line-by-line manipulation is implemented by the well developed ultrashort pulse shaping techniques [3] using a fiber coupled Fourier-Transform pulse shaper which incorporates a 2x128 pixel liquid crystal modulator (LCM) array to independently control both amplitude and phase of each spectral line. The individual pixels of the LCM can be electronically controlled to give an arbitrary amplitude modulation and a phase shift in the range of 0 to  $2\pi$ . In order to achieve line-by-line pulse shaping, great care is taken in the pulse shaper design to improve resolution. A fiber coupled pulse shaper with a reflective geometry [5] is built, which includes a collimator and telescope combination to produce a collimated beam with  $\sim 18$  mm diameter, an 1100 grooves/mm grating, a lens with 750 mm focal length, an LCM with a 12.8 mm aperture and 2x128 independent pixels, a retro-reflecting mirror, and a circulator. The fiber coupled input-output loss of the pulse shaper is 15 dB. The measured resolution (frequency range affected by an individual LCM pixel) agrees well with the calculated value of 8.5 GHz. To the best of our knowledge, this is the highest resolution ever reported for a grating based pulse shaper.

Our experiments are performed using a home-built harmonically mode-locked fiber laser followed by a dispersion decreasing fiber soliton compressor producing  $\sim 0.4$  ps pulses at 1542 nm center wavelength with

repetition rate that can be tuned between 8 GHz and 13 GHz. Fig. 2(A) shows a portion of the power spectrum when the laser is tuned for 8.5 GHz repetition rate without amplitude or phase modulation from the pulse shaper. The optical linewidths are limited by the 0.01 nm resolution of the optical spectrum analyzer used for this measurement. Importantly, even without active stabilization, at 8.5 GHz repetition rate the absolute frequency positions of the individual spectral lines are stable to within the measurement resolution for periods of tens of minutes. This makes possible stable line-by-line pulse shaping experiments. For example, Fig. 2 (B) demonstrates line-by-line amplitude control by programming the LCM to block every other spectral line. In this example, the blocked spectral lines are almost completely suppressed while the transmitted lines remain essentially untouched, which clearly illustrates that line-by-line pulse shaping with an excellent resolution of 8.5 GHz has been achieved.

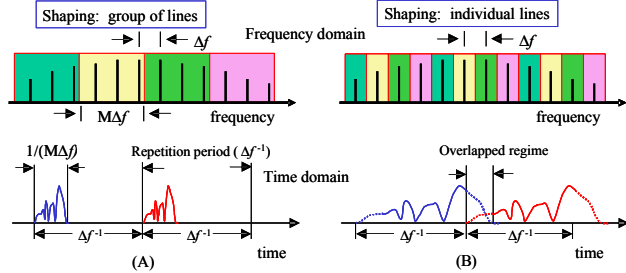


Fig. 1. Illustration of pulse shaping (A) Manipulating groups of lines. (B) Manipulating individual lines.

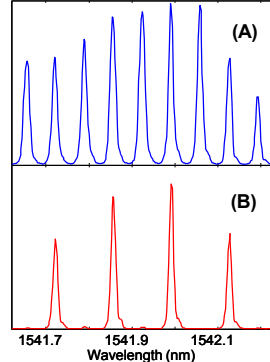


Fig. 2. (A) Spectral lines without amplitude modulation. (B) Amplitude modulation by blocking every other line.

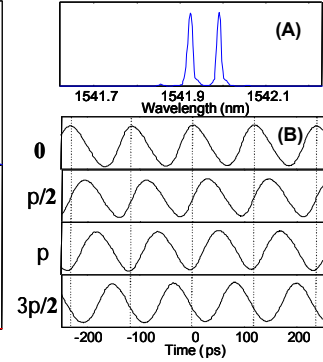


Fig. 3. (A) Two spectral lines. (B) Sampling scope traces with phase modulation (0,  $\pi/2$ ,  $\pi$  and  $3\pi/2$ ) on one spectral line. The traces are the average of 100 measurements.

Fig. 3 demonstrates the capability of line-by-line phase control by phase shifting one of two spectral lines. Fig. 3(A) shows two spectral lines while blocking all other lines by programming the pulse shaper. The effect of spectral phase can be observed directly in the time domain. Since there are only two spectral lines, ideally the waveform in the time domain corresponds to a cosine function in which the temporal phase of the cosine function is determined by the relative spectral phase between the two spectral lines. Mathematically, ignoring any broadening of the spectral lines, the field in the frequency domain can be expressed as

$$A(f) = d(f - e) + b \delta(f - \Delta f - e) \exp(-j\Phi) \quad (2)$$

where  $\delta(\cdot)$  represents the impulse function,  $b$  and  $\Phi$  represent the relative amplitude and phase between the two spectral lines which can be independently controlled with the pulse shaper. In the time domain, the intensity profile can be obtained by Fourier Transform as

$$|a(t)|^2 = 1 + b^2 + 2b \cos(2p\Delta f t - \Phi) \quad (3)$$

Clearly, the intensity profile is a cosine function of frequency  $\Delta f$ . This can be simply understood as laser pulses broadened to cosine waveforms extending to the whole repetition period by filtering to only two spectral lines. Fig. 3(B) shows the intensity profiles of waveforms in the time domain – detected by a 50 GHz photodiode and measured by a sampling scope (averaged 100 times). All four waveforms indeed show a cosine function with a temporal phase shift which is induced by the spectral phase shift applied to one of the two spectral lines in the pulse shaper – here 0,  $\pi/2$ ,  $\pi$  and  $3\pi/2$  relative phase shift are demonstrated. More importantly, the phase of  $a(t)$  can be calculated as (let  $b=1$  to simplify the result)

$$\text{angle}(a(t)) = 2p(e + \frac{\Delta f}{2})t - \frac{\Phi}{2} \quad (4)$$

which is related to comb-offset frequency  $e$ . As a result, fluctuations in comb-offset frequency  $e$  cause fluctuations in the phase and therefore the interference in overlap region, which are demonstrated in following experiments.

Intuitively, line-by-line pulse shaping requires a stable mode-locked laser source, especially stable spectral lines. In our system, when the laser is operating at an 8.5 GHz repetition rate we observe relatively stable performance, which makes line-by-line pulse shaping possible as shown in Fig. 2 and Fig. 3. To investigate this issue further, we have repeated the line-by-line phase control experiment and recorded both the optical spectra and sampling scope traces consecutively to show their fluctuations. Fig. 4(A) and Fig. 4(B) show an overlap of 100 scans for the two spectral lines and sampling scope traces for 8.5 GHz pulse repetition rate, which show relatively stable features. If there is no pulse shaping (corresponding to 0 phase shift), the sampling scope traces are clear. If there is pulse

shaping with a  $\pi$  phase shift on one spectral line, the sampling scope traces become slightly noisy due to the small fluctuations of spectral lines as shown in Fig. 4(A). Nevertheless, the spectral lines seem stable enough for line-by-line control as demonstrated above.

When we tune the laser source to 11.0 GHz repetition rate, we observe empirically that the absolute frequency positions of the spectral lines become considerably less stable, as shown in Fig. 5(A), with frequency fluctuations observable on the time scale of seconds. We attribute the difference in optical frequency stability at different laser repetition rates to the frequency dependent response of the microwave components used for feedback control of the cavity length. This allows us to investigate the role of optical comb frequency fluctuations on line-by-line shaping. If there is no pulse shaping (corresponding to 0 phase shift), the sampling scope traces are clear even if the spectral lines are relatively unstable as shown in Fig. 5(B). However, if there is pulse shaping with a  $\pi$  phase shift on one spectral line, the sampling scope traces become very noisy due to the large fluctuations of the spectral lines, which is a much more significant effect compared to the 8.5 GHz repetition rate results. This result can be understood by the overlapping effect: for  $\pi$  phase shift, the original laser pulses (corresponding to 0 phase shift) are broken up to form new pulses (corresponding to  $\pi$  phase shift) in the temporal region where contributions from adjacent input pulses overlap. Since the adjacent original pulses have an unstable phase relationship (intimately related to unstable spectral lines), their interference in the overlapped region leads to large fluctuations. Much weaker fluctuations, if any, are observed at the time locations of the original input pulses, since there is little temporal overlap at those times. Clearly, this overlapping effect leads to observation of a new time-dependent noise process, directly linked to variations in the spectral line position.

We also implement line-by-line pulse shaping for multiple spectral lines (corresponding to short pulses instead of cosine waveform). Fig. 6 (A) shows the intensity cross-correlation measurement at 8.5 GHz repetition rate. Without shaping, short pulses (black curve) are well isolated. By applying spectral phase manipulation on multiple spectral lines, the broadened pulses (red and blue curves) clearly overlap with each other. In the overlapped region as shown in Fig. 6(B) the measured waveforms are essentially reproducible, consistent with the relatively clear sampling scope trace in Fig. 4 (B). In contrast, at 11.0 GHz repetition rate with relatively unstable spectral lines, the shaped pulses exhibit fluctuating structures in the overlapped region as shown in Fig. 7. Again, this demonstrates that fluctuations in the comb-offset frequency give rise to fluctuating interference in overlapped time regions caused by pulse shaping.

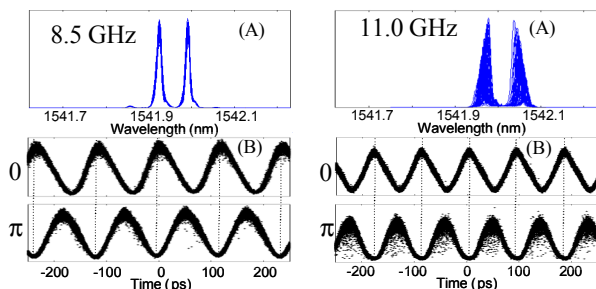


Fig. 4. (A) Two relatively stable spectral lines at 8.5 GHz. (B) Sampling scope traces with phase modulation (0 and  $\pi$ ) on one spectral line. The traces are scanned 100 times.

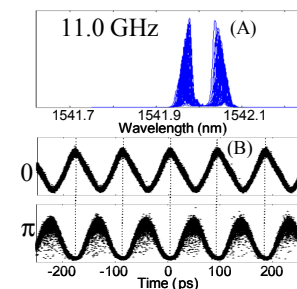


Fig. 5. (A) Two relatively stable spectral lines at 11.0 GHz. (B) Sampling scope traces with phase modulation (0 and  $\pi$ ) on one spectral line. The traces are scanned 100 times.

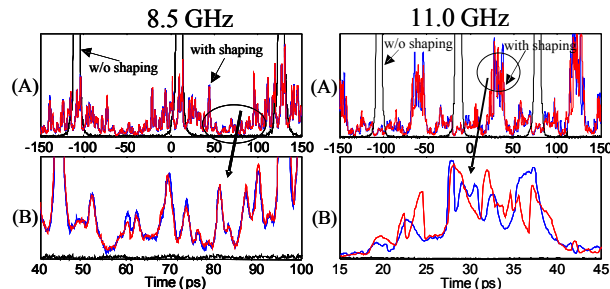


Fig. 6. (A) Intensity cross-correlation traces at 8.5 GHz for multiple spectral lines. Black: pulse without shaping. Red and blue: pulse with shaping. (B) Details in overlapped region.

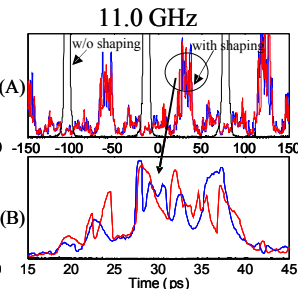


Fig. 7. (A) Intensity cross-correlation traces at 11.0 GHz for multiple spectral lines. Black: pulse without shaping. Red and blue: pulse with shaping. (B) Details in overlapped region.

In summary, we have experimentally demonstrated spectral line-by-line pulse shaping with an actively mode-locked fiber laser using a high resolution pulse shaper. The shaped pulses overlap with each other, which leads to observation of a new time-dependent noise process, directly linked to variations in the comb-offset frequency.

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