

Real-Time Adaptive Amplitude Feedback in an AOM-Based Ultrafast Optical Pulse Shaping System

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Abstract—We demonstrate real-time adaptive amplitude feedback in an AOM-based ultrafast optical pulse shaping system operating at $\lambda = 1550$ nm wavelength for optical communication applications. At the optimized feedback depth, a simple negative feedback algorithm converges in fewer than 10 iterations to within 5% of the target shape. This technique may be very useful for many applications including spectrum-sliced WDM.

Index Terms—Acousto-optic modulation, feedback, optical pulse shaping, ultrafast optics, wavelength-division multiplexing.

THE AOM-based optical pulse shaper uses shaped acoustic pulses to generate the programmable spatial light modulation patterns [1]–[3]. The update rate is determined by the aperture-filling time of the AOM. The response time, on the other hand, is determined by the modulation bandwidth of the AOM. Ultrahigh-throughput (>1 Tb/s) network architectures have been proposed based on AOM pulse shaping and other ultrahigh bandwidth all optical technologies [4]. High-speed (~ 500 -Gb/s) data operations, such as ultrahigh-ratio data compression [1], have also been demonstrated using AOM pulse shaping. In these AOM-based pulse shaping applications, active feedback can reduce most of the unwanted distortions. Here, we demonstrate feedback in an AOM-based pulse shaping system. At the optimized feedback depth, a simple negative feedback algorithm converges in fewer than 10 iterations to within 5% of the target shape, and achieves a greater than 200% increase of the 3-dB bandwidth.

Since SLM-based pulse shaping technologies [5], [6]—including the AOM-based ones we used here—can manipulate the ultrafast laser pulse spectrum over its inherently wide optical bandwidth, a single fiber-ring mode-locked laser, which generates ultrafast laser pulses at 1550 nm with >10 -THz spectral bandwidth, can be spectrally sliced to provide the multichannel optical source for spectrum-sliced WDM schemes [4], [7]–[12]. Power equalization for different WDM channels, like trace (a) in Fig. 1, is often not simple. The output pulse spectrum of high output power fiber-ring mode-locked lasers can be quite irregular, as shown by the trace (b) in Fig. 1, which is a typical output spectrum of the ErF laser (from Clark-MXR, Inc.) used here. Adaptive real-time amplitude feedback for the AOM-based pulse shaping can modify an arbitrary input spectrum and make it within a preset tolerance level (5% in our case) of an arbitrary target shape in fewer

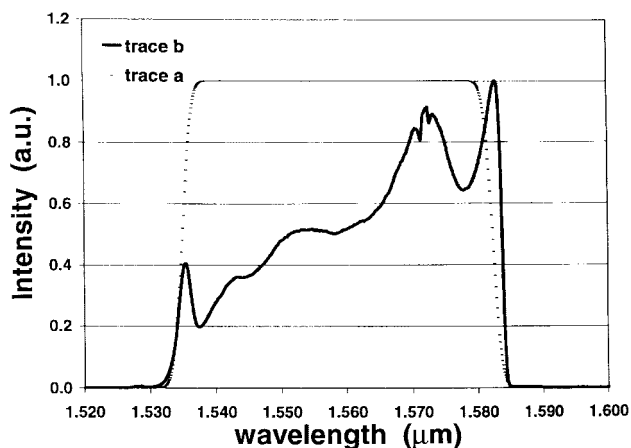


Fig. 1. Desirable flat-topped broadband spectrum (trace a) versus usually broadband but irregular spectrum of the ultrafast laser pulses generated from fiber ring mode-locked lasers (trace b).

than 10 iterations of the feedback loop, as long as the optical source provides the spectral components required by the target.

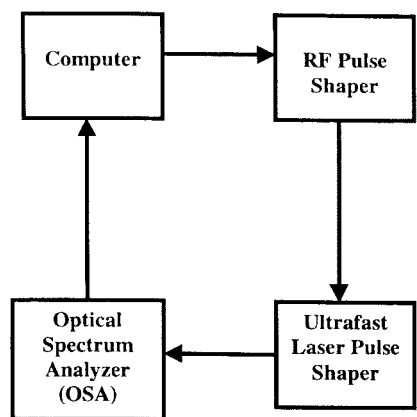
The experimental setup and the feedback algorithm are delineated in Fig. 2. In Fig. 2(a), an optical spectrum analyzer (OSA, HP71451B) collects the intensity spectra of the shaped pulses with a bandwidth resolution of 1-nm. A 200 MHz dual-channel arbitrary waveform generator (AWG, LeCroy 9109) is used to generate the amplitude modulation (AM) that is put onto an RF carrier wave of 150 MHz using a simple RF mixer circuit [6]. The AWG is configured in single channel output mode to maximize the modulation speed for amplitude-only modulations. The RF AM signal is then amplified to a power level of approximately 32 dBm (peak) and is delivered into the 50- Ω RF input port of the large aperture AO modulator (Brimrose, Inc.). It takes the acoustic wave generated by the RF signal about 4 μ s to traverse the clear aperture (about 20 mm) of the AOM crystal. This 4- μ s RF time window corresponds to a spectral range of 86 nm for the laser pulses. A central computer receives the intensity spectra from the OSA via a GPIB board and updates the modulation function using the simple negative feedback algorithm illustrated in Fig. 2(b).

The algorithm starts by taking the spectrum of the laser pulse shaped by an initial RF modulation function from the OSA and then normalizes it. The normalized spectrum is then compared with the target shape (also normalized). The difference is then multiplied by a feedback depth factor, and then added back to the normalized RF modulation pattern using negative feedback. The rescaled RF modulation function is transmitted to the AWG via the GPIB board and then

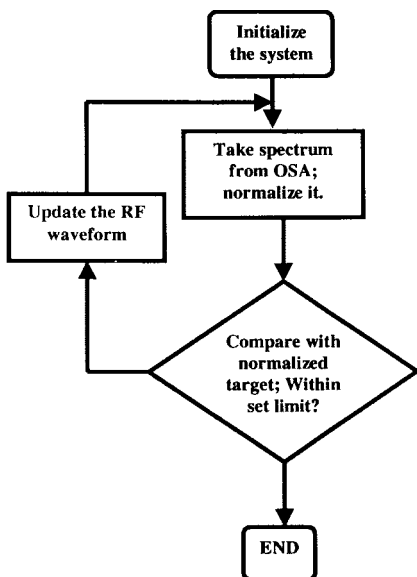
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(a)

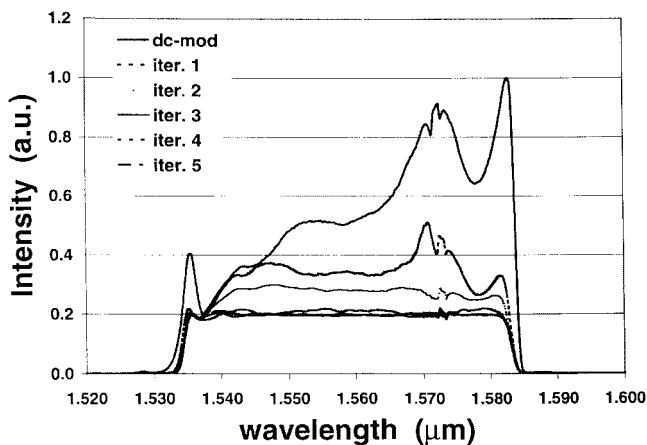


(b)

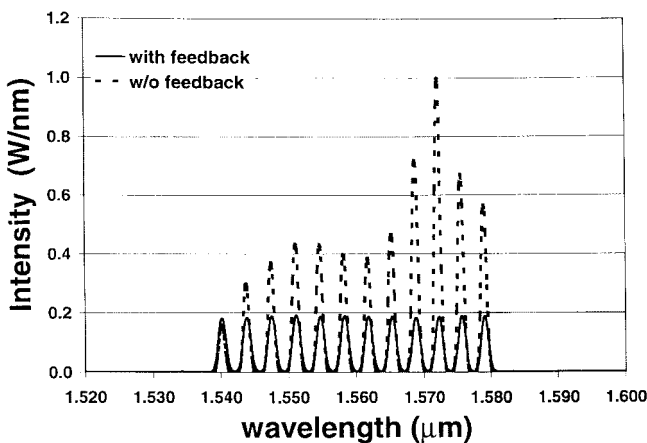
Fig. 2. Feedback loop implemented. (a) Block diagram of experimental setup. (b) Block diagram of computer feedback program.

delivered to the programmable optical pulse shaper, which updates the pulse intensity spectrum. This process is repeated until the measured intensity spectrum converges to the target shape within the preset tolerance level.

Experimental results of the amplitude feedback in this AOM-based optical pulse shaping system are shown in Fig. 3. In Fig. 3(a), the intensity spectra after each of the first five iterations are shown along with the original input spectrum. It can be seen that using the optimal feedback depth, it only takes 5 to 7 iterations to bring the input spectrum to within 5% of the target shape. Without optimization of the feedback depth, it usually takes about 30 iterations for the 5% tolerance level to be reached. Fig. 3(b) compares a spectrum-sliced multichannel WDM source with and without the adaptive amplitude feedback. The effect of channel equalization is significant. In terms of 3-dB bandwidth improvement, a >200% increase is achieved. The total energy throughput of the AOM-based pulse shaper is about 15% due to the AO diffraction efficiency. It is noticed, however, that since the feedback scheme implemented here is optically passive, the equalization



(a)



(b)

Fig. 3. (a) Fast convergence to the targeted flat-topped spectral shape within five iterations of the feedback loop. (b) Spectrum-sliced WDM channels with/without feedback equalization.

simply throws away the extra spectral energy that is above the lowest level within the selected spectral range. Apart from this unavoidable energy loss, there is almost no extra loss due to the implementation of the feedback itself. Currently, the OSA in the feedback loop takes about 500-ms scan time to collect the pulse spectrum, and this limits the actual update rate of the system. This limitation, however, is not fundamental, and can be significantly improved when a detector-array based single shot spectrometer is employed. The fundamental limit of the update rate is the update rate of the AOM, which in our case is about 4 μ s.

This real-time adaptive amplitude feedback automatically accomplishes the precompensation (or predistortion) that is necessary to overcome the major nonidealities in the AOM-based ultrafast pulse shaping system. These issues include, among others, the inhomogeneous diffraction efficiency along the crystal aperture, the deviation of the AOM and/or its driving circuits from a linear response, and the nonideal input spectrum. This feedback technique can also be used inside a laser cavity to achieve flexible spectral gain control, which is desired in many applications. This technique is adaptive in the sense that it does not require the knowledge of the AOM's characteristic responses, which can be different even among

the same type of devices and, due to practical difficulties, can not readily be fully characterized. Real-time feedback scheme can also overcome other common nonidealities like the drifting effects of a laser system, such as spectral drift. Finally, since AOM-based optical pulse shaping uses travelling acoustic waves to modulate the laser pulse spectrum, the timing of the shaped laser pulses and the mapping between the RF time and the laser wavelength [3] are critical. Correct synchronization and precise spectral-temporal mapping can be easily found by using this feedback technique. In practice, the residual mismatch in this mapping and the finite spectral resolution of the system determine the lower limit of the achievable tolerance level.

The approach presented here compares favorably in many respects to other spectral power equalization methods. For example, mechanical antireflection switch (MARS) micromechanical modulators have been used as spatial light modulators and dynamic spectral power equalization has been demonstrated with $<10 \mu\text{s}$ response time. Closed-loop feedback, however, is still desirable in order to compensate possible attenuation drift [13]. One-step power equalization has also been demonstrated in an integrated device involving waveguide grating routers (WGR). It uses multielement phase shifters as spatial light modulators, and a Mach-Zehnder interferometer configuration to achieve phase-to-intensity conversion [14]. However, active feedback or feed-forward is still desired in order to cope with the possible changes that could alter the system transfer function over time or temperature. Finally, an active feed-forward channel equalization scheme has been demonstrated for CPWDM, giving approximately a 50% increase of the 3-dB bandwidth [9].

Several other groups have also recently reported adaptive feedback schemes in optical pulse shaping systems [15]–[22], generally with the goal of wavepacket manipulation or coherent control. When LCM-array-based pulse shaping is used [16]–[21] the updating rate is limited by the reorientation time of the liquid-crystal molecules, which is typically on the order of 50 ms [6]. In AOM-based pulse shaping, the updating rates are several orders of magnitude faster than that of LCM-array-based pulse shapers [6], and a single modulator can control both amplitude and phase. Commercially available liquid crystal arrays currently have also far fewer pixels than AOM-based optical pulse shapers.

In summary, we presented in this letter a real-time adaptive amplitude feedback in the AOM-based ultrafast optical pulse shaping system operational in the 1550-nm wavelength range. Using the optimal feedback depth, the simple negative feedback algorithm converges in fewer than 10 iterations to within 5% of the target shape. This technique can be very useful for many applications including spectrum-sliced WDM in optical telecommunications.

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