Towards an all-Fiberized GHz Self-Referenced Electro-Optic-Modulated Comb

Lawrence Robert Trask*, Srinivas Varma Pericherla, Peter J. Delfyett**
CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida, 32816, USA
**lawrencetrask@knights.ucf.edu, **delfyett@creol.ucf.edu*

Abstract: We present a new cost-effective, fiberized architecture for generating low noise, sub-100 fs, 12 kW peak power pulses using GHz spaced, filtered electro-optic modulated combs (>70dB OSNR), and nonlinear-pulse-shaping.

1. Introduction

Optical frequency combs are revolutionizing many fields such as spectroscopy, metrology, and ultra-wideband communications [1]. This is in part due to their simplicity in detection and the widespread techniques that have been developed to stabilize them with microwave precision. Each comb line can be traced to the simple relationship: $f=f_{ceo}+nf_{rep}$. Where f_{rep} is the repetition rate of the pulsed source and f_{ceo} is the carrier phase to envelope slip between each pulse. The ability to measure and control both variables gives access to the extreme stability optical frequency combs can provide. Commercial photodetectors today can measure $f_{rep}<100$ GHz through simple illumination whereas f_{ceo} requires more complexity. Precise measurements of f_{ceo} typically employ extremely large optical bandwidths on the order of ~100 THz in conjunction with nonlinear optics. Previous works of generating tens of GHz repetition rate optical frequency combs at 1550 nm used a CW laser followed by a cascade of electro-optic modulators; producing an electro-optic modulated (EOM) comb [2], [3]. The EOM comb is then used as a seed for octave spanning coherent supercontinuum generation. Difficulties in producing octave spanning coherent supercontinuum generation with EOM combs include: obtaining 100 fs pulses with at least 10 kW peak power and optically filtering the combs [3]. In our work, we lock and filter all of the EOM comb lines to a 100k finesse etalon with ~1.5 GHz free spectral range. This technique stabilizes and filters every comb line to an ultra-stable reference etalon with a ~15 kHz passband. Ultrashort pedestal free pulses are then generated by using a nonlinear optical loop mirror (NOLM) [4], and a nonlinear amplifying loop mirror (NALM) [5]. Since the nonlinear-pulse-shaping is done inside fiber, the cost of such an approach is relatively cheap. The combination of these two systems allows for a low noise, GHz, repetition rate scalable, completely fiberized, and cost-effective approach to generating high peak power pulses suitable for octave spanning coherent supercontinuum generation.

2. Experimental Setup and Results

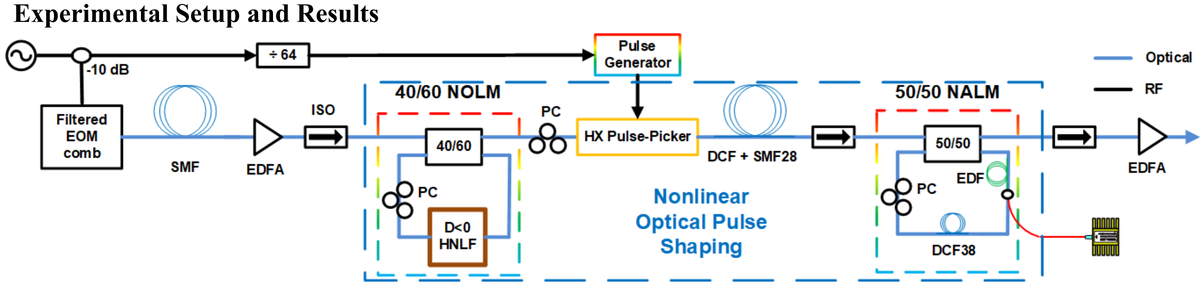

Fig. 1. Schematic diagram of a filtered/locked EOM comb and nonlinear pulse shaping for ~100 fs pulses. EDFA: erbium doped fiber amplifier, HX Pulse-picker: high extinction electro-optic modulator, D<0 HNLF: normal dispersion highly nonlinear fiber, EDF: erbium doped fiber, PC: polarization controller.

Our architecture combining both nonlinear-pulse-shaping and optical filtering is shown in fig. 1. Details of the locked and filtered EOM comb can be found in [6]. The microwave drive frequency was set to 10.4869952 GHz, which is exactly seven times the FSR. After generation of the locked and filtered EOM comb, SMF28 is used to compress the EOM comb pulses before amplifying them to .6 W in a commercial EDFA. The commercial EDFA is spliced directly to a 40/60 NOLM which simultaneously broadens the optical spectrum and shapes the temporal intensity. The NOLM consists of normal dispersion highly nonlinear fiber (D<0 HNLF), fiber pigtailed polarization controller, 40/60 coupler, and SMF28. The pulse train is then pulse-picked down by a factor of 64. Pulse-picking reduces the duty-cycle of the pulse train, allowing for higher peak powers after amplification. A section of dispersion compensating fiber (DCF) and SMF compress the pulses prior to the NALM. The NALM eliminates the residual temporal sidelobes in the pulse, reduces pulse-picker noise, and provides gain for the pulse train. The

NALM consists of a short length of erbium doped fiber, 50/50 coupler, 980/1550 WDM, DCF, fiber pigtailed polarization controller, and SMF28. The output of the NALM is sent through a home built EDFA for nonlinear spectral broadening and subsequent pulse compression in SMF28 where the average power was measured to be 158 mW. Diagnostic traces of our system are shown below in fig. 2.

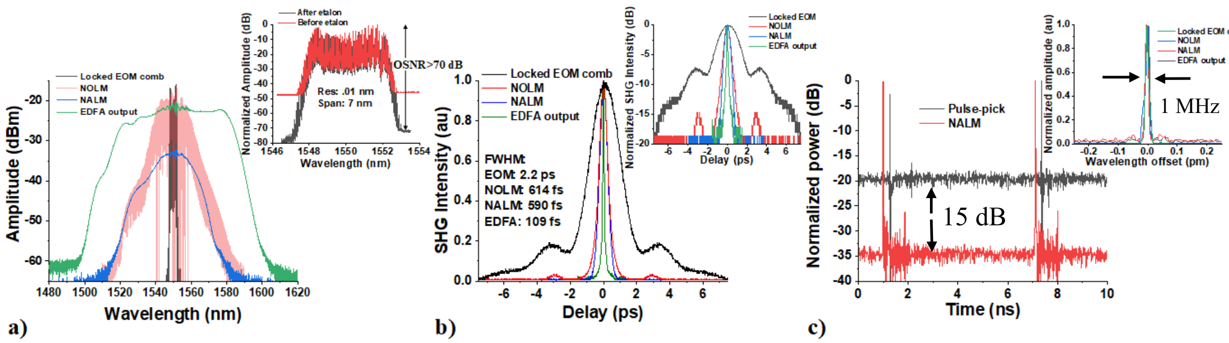

Fig. 2. Diagnostic traces showing a) optical spectrum b) intensity autocorrelation after the etalon, NOLM, NALM, and home built EDFA. Sampling scope trace c) after pulse-picking and after the NALM. Inset of a, optical spectrum before and after 100k finesse etalon. Inset of b, intensity autocorrelation in log scale. Inset of c, linewidth measurement using high resolution OSA.

After optical locking and filtering of the EOM comb, the OSNR exceeds 70 dB (inset of fig. 2a). Despite spectral filtering of the EOM comb, large temporal sidelobes can be seen in the intensity autocorrelation fig. 2b. Since our EOM comb only has two high RF power handling and low V_π phase modulators, it produces pulses with an intensity autocorrelation FWHM of 2.2 ps. After the 40/60 NOLM, the intensity of the temporal sidelobes has been significantly reduced and the intensity autocorrelation FWHM drops to 614 fs (without compression). After the NALM, the optical spectrum of the EOM comb has been fully reshaped into a pulse spectrum with no temporal sidelobes with an intensity autocorrelation FWHM of 590 fs (without compression). This can be seen in the intensity autocorrelation (fig. 2b and inset of fig. 2b) where the temporal sidelobes have been fully removed on both a linear and dB scale. The pulse train after pulse-picking and after the NALM are shown in fig. 2c. By using a NALM after pulse-picking, our extinction ratio after pulse-picking increases by 15 dB (as shown in fig. 2c). This further reduces the duty cycle of the pulse train and improves the amplitude noise performance of our system. As a testament to the low noise properties of our system, we used a high-resolution OSA (HR-OSA) to measure the comb tooth linewidth of the EOM comb at 1550nm, the NOLM comb tooth linewidth at 1530 nm, NALM comb tooth linewidth at 1530 nm, and EDFA output comb tooth linewidth at 1520 nm (inset of fig. 2c). The linewidth measurement in all cases was limited by the resolution of the HR-OSA (1 MHz), showing no appreciable degradation of the comb tooth linewidth after pulse-picking and nonlinear spectral broadening. The combination of low noise and high contrast pulses allows for pedestal free amplification of the pulse train, giving rise to an intensity autocorrelation FWHM of 109 fs. Using a deconvolution factor of 1.4, which is comparable to that of a parabolic pulse spectrum as shown in fig. 1a. The pulse duration can be inferred to be sub-100 fs (78 fs) with a peak power of at least 12 kW.

3. Conclusion

We have demonstrated a new approach to generating sub-100 fs pulses with 12 kW peak power from a filtered EOM comb using a modified PDH setup and nonlinear-pulse-shaping. The modified PDH setup stabilizes and filters all of the comb lines in the EOM comb to an ultra-stable reference. The NOLM and NALM perform temporal pulse shaping for pedestal removal and enhance the extinction ratio of the pulse-picker by 15 dB. All components in our system are available with fiber coupling. We believe this architecture will provide for a low noise, GHz, repetition rate scalable, completely fiberized, and cost-effective approach to obtaining coherent octave spanning supercontinuum generation.

4. References

[1] Diddams, Scott A. "The evolving optical frequency comb." *JOSA B* 27.11 (2010): B51-B62.
[2] Ishizawa, A., et al. "Carrier-envelope-offset locking of 25-GHz EOM comb based on a free-running CW Laser Diode." *2018 Conference on Lasers and Electro-Optics (CLEO)*. IEEE, 2018.
[3] Beha, Katja, et al. "Electronic synthesis of light." *Optica* 4.4 (2017): 406-411.
[4] Doran, N. J., and David Wood. "Nonlinear-optical loop mirror." *Optics letters* 13.1 (1988): 56-58.
[5] Fermann, Martin E., et al. "Nonlinear amplifying loop mirror." *Optics Letters* 15.13 (1990): 752-754.
[6] Trask, Lawrence, et al. "Hyperfine Filtering of an Electro-Optic Modulated Comb." *2020 IEEE Photonics Conference (IPC)*. IEEE.