3.5-THz Wide, 175 Mode Optical Comb Source

R. P. Scott, N. K. Fontaine, J. P. Heritage, B. H. Kolner and S. J. B. Yoo

Department of Electrical and Computer Engineering,
University of California, Davis, California 95616
sbyoo@ucdavis.edu

Abstract: A stable 3.5-THz wide (175 modes × 20 GHz) optical comb source with nearly flat spectral phase is demonstrated. Adjustable mode spacing and wavelength tunability across the C-band are maintained.

OCIS codes: (060.5530) Pulse propagation and solitons; (320.5520) Pulse compression; (320.7100) Ultrafast measurements

1. Introduction

Recently, applications such as optical arbitrary waveform generation (OAWG) [1], ultra-stable multi-wavelength sources, and photonic microwave waveform generation have driven the demand for extremely stable optical frequency combs [2]. In general, these combs need to have repetition rates in the GHz or even tens of GHz range. Although extremely stable sources, such as carrier-enveloped offset (CEO) locked Ti:sapphire lasers have been demonstrated, the need for flexible and less expensive alternatives has not been met. At telecommunications wavelengths, repetition rates in the GHz regime are available through harmonically modelocked fiber lasers or fundamentally modelocked laser diodes. However, they typically do not have the required wavelength stability or repetition rate adjustability.

Optical comb generation based on strong modulation of single frequency lasers has proven to be suitable for many applications. Recent improvements in ultrastable, narrow linewidth tunable lasers and broadband modulators have enabled very flexible, yet stable, optical comb generators. However, the number of directly generated modes has been limited to less than 30 [3]. Optically resonant structures (e.g., Fabry-Perot cavities) placed around the optical frequency comb generator (OFCG) have been used to generate hundreds of modes [4]; however these schemes are complex and sacrifice the repetition rate (mode spacing) flexibility. Additionally, it has been shown that resonant OFCG's can be used to drive dispersion flattened fiber to produce wide bandwidths [5], but the output of the fiber is a distorted pulse with nonlinear chirp and would be particularly sensitive to laser noise [6]. This paper demonstrates a simple and relatively inexpensive technique which maintains much of the flexibility and stability of the original OFCG yet provides a 3.5-THz wide optical comb with nearly flat spectral phase. It uses soliton-like compression in dispersion decreasing fiber (DDF) to generate the 175 optical modes. This technique is demonstrated with 10- and 20-GHz mode spacing, but would work equally well at repetition rates from 5 to 30 GHz or more (peak power and pulse width should be kept similar, upper frequency limited by stimulated Brillouin scattering). The wavelength tunability is only restricted by the efficiency of the DDF compression, but will certainly operate over most of the C-band. The flat phase of the output spectrum makes this source particularly attractive for OAWG applications.

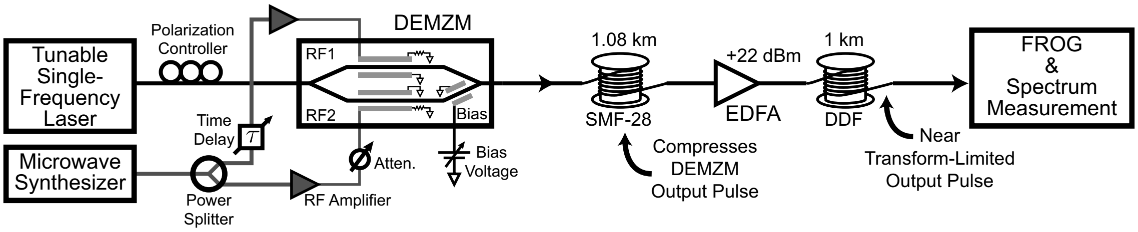

Fig. 1. Experimental arrangement for widely tunable optical frequency comb generation using soliton-like compression in DDF. DEMZM: dual-electrode Mach-Zehnder modulator.

2. Experimental Setup

The arrangement used to generate a 3.5 THz optical comb at 1550 nm is shown in Fig.1 and consists of an OFCG, compression fiber, optical amplifier and DDF. The comb generator utilizes a dual-electrode Mach-Zehnder modulator (DEMZM) to simultaneously amplitude and phase modulate (AM/PM) a single frequency laser (Anritsu MG9638A) and create a flattened comb with 20-GHz spacing [3]. RF1 of the DEMZM is driven at +27 dBm and RF2 is driven at +25 dBm. The output pulses of the OFCG are highly frequency chirped and the sign of the chirp is determined by the phase difference between RF1 and RF2. The sign of the output chirp is chosen so that standard single mode fiber (SMF-28) will remove most of the chirp, thereby compressing the pulses to approximately 5 ps. An erbium-doped fiber amplifier (EDFA) amplifies the pulses to an average power of +22 dBm before they are launched into the DDF. The 1-km DDF (PriTel, DDF-400) has an input dispersion of 9.8 ps/nm and it linearly decreases to 2.1 ps/nm at the output [7]. It is optimized for transform-limited input pulses with widths of 2.5 to 5 ps.

The optical comb was characterized with both a high resolution spectrometer (Agilent 83453A) and frequency resolved optical gating (FROG) [8]. The spectrum analyzer was set to a resolution of 250 MHz/point and had a dynamic range of ~45 dB. FROG measurements of the comb were made using cross-correlation FROG (XFROG) with the optical modes spectrally resolved [8].

3. Results and Discussion

The DEMZM output is a highly chirped pulse with nine optical modes as shown in Fig. 2. The output pulse width is approximately 20 ps and the chirp is a result of the sinusoidal modulation applied by the DEMZM and inherent to OFCG. This pulse is then compressed by the SMF to the waveform shown in Fig. 3, before amplification and launching into the DDF. The compressed pulse width is 5 ps and the phase is nearly flat, indicating a transform-limited pulse which is necessary for optimum compression in the DDF.

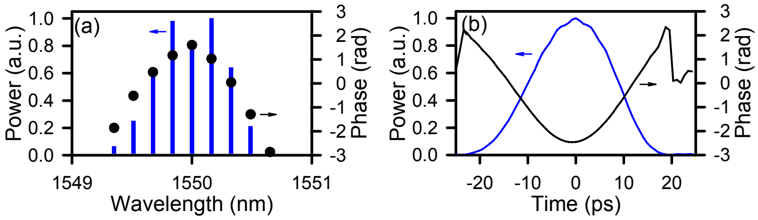

Fig. 2. Highly chirped output directly from the DEMZM. (a) Retrieved spectral mode intensity (solid lines) and phase (filled circles). (b) Retrieved temporal intensity (blue) and phase (black).

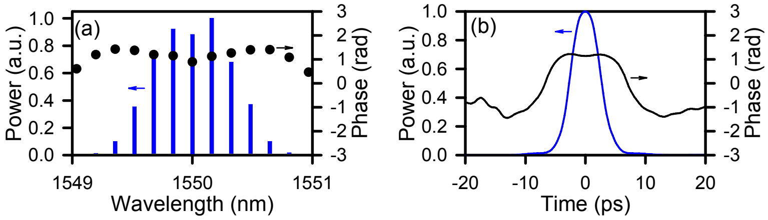

Fig. 3. DDF input is a near transform-limited pulse after compression in SMF-28. (a) Retrieved spectral mode intensity (solid lines) and phase (filled circles). (b) Retrieved temporal intensity (blue) and phase (black).

After soliton-like compression in the DDF, the pulse contains 175 optical modes as shown in Fig. 4. These data were taken with a heterodyne-type, high-resolution spectrometer (250 MHz/point) that gives us the ability to easily resolve the spectral modes and verify that the optical signal-to-noise ratio (OSNR) had not significantly degraded. In fact, the DDF output OSNR is the same as the single frequency laser (~40 dB).

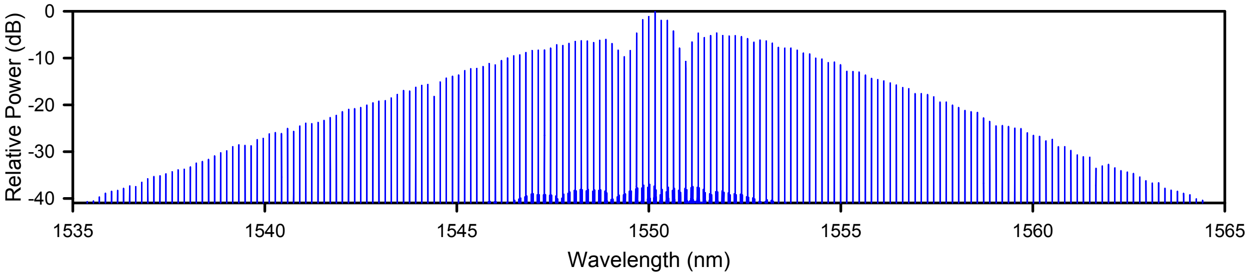

Fig. 4. High-resolution (250 MHz/pt) spectral scan of the DDF output showing all 175 modes with 20-GHz spacing.

Fig. 5 shows the retrieved spectral and temporal intensity and phase. The phase is nearly flat, indicating a transform-limited pulse with a width of less than 500 fs (FWHM). Comb lines below -30 dB are not shown because the FROG measurement has a dynamic range of 35 dB and the retrieved mode amplitudes and phases below -30 dB are imprecise.

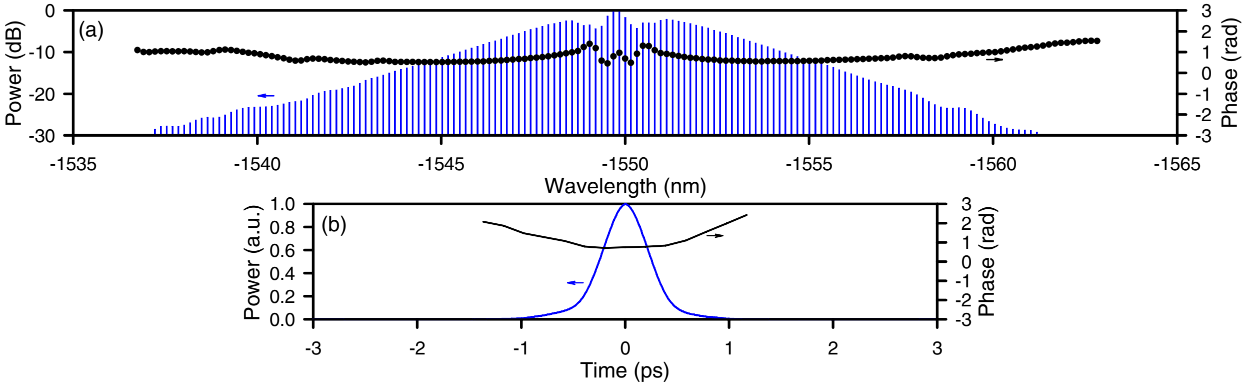

Fig. 5. Output from DDF retrieved by FROG showing nearly flat spectral phase. (a) Retrieved spectral mode intensity (solid lines) and phase (filled circles). (b) Retrieved temporal intensity (blue) and phase (black).

The wavelength and repetition rate tunability is demonstrated by Fig. 6. The center wavelength of the laser was adjusted to 1530 nm for the data shown in Fig. 6(a). The higher output power at this wavelength allows significantly more power per mode to be generated than at 1550 nm, with nearly 150 modes above -20 dBc. The spectrum shown in Fig. 6(b) was taken with repetition rate set to 10 GHz. The reduced contrast is due to the resolution (0.05 nm or 6.25 GHz) of the optical spectrum analyzer (OSA). However, over 300 modes are shown in Fig. 6(b). One characteristic of DDF compression is apparent in all of the DDF output spectra; dips in the spectrum near the center wavelength. These dips appear due to interference between the short compressed pulse and the spectrally-narrow pedestal.

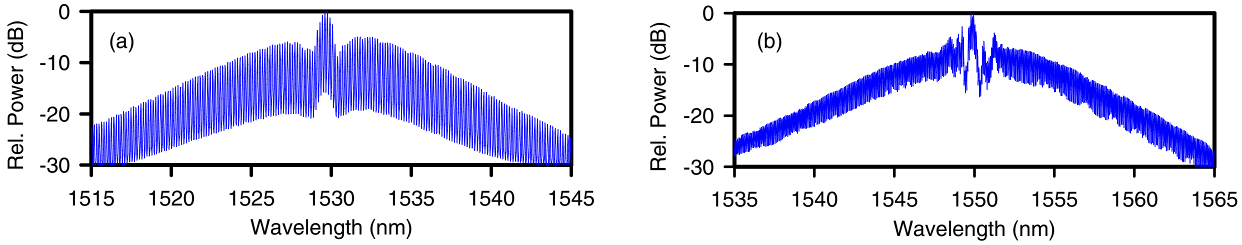

Fig. 6. Spectrum of the DDF output demonstrating the OFCG tunability. (a) Tunable laser output centered at 1530 nm (20-GHz mode spacing). (b) 10-GHz mode spacing centered at 1550 nm. OSA resolution is 0.05 nm or 6.25 GHz.

4. Conclusion

This paper demonstrates a 3.5-THz wide optical frequency comb generator with wavelength and comb spacing tunability. Nearly flat spectral phase of the output spectra is achieved by DDF compression of a non-resonant OFCG and results in 175 optical modes with 20-GHz spacing, and 300 optical modes with 10-GHz spacing, tunable over most of the C-band. The flat spectral phase, simplicity and tunability make this source very attractive for OAWG applications.

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