Generation of a 660–2100 nm laser frequency comb based on an erbium fiber laser

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We present a multibranch laser frequency comb based upon a 250 MHz mode-locked erbium-doped fiber laser that spans more than 300 THz of bandwidth, from 660 nm to 2100 nm. Light from a mode-locked Er:ﬁber laser is ampliﬁed and then broadened in highly-nonlinear ﬁber to produce substantial power at ∼1050 nm. This light is subsequeotly ampliﬁed in Yb:ﬁber to produce 1.2 nJ, 73 fs pulses at 1040 nm. Extension of the frequency comb into the visible is achieved by supercontinuum generation from the 1040 nm light. Comb coherence is veriﬁed with cascaded f−2f interferometry and comparison to a frequency stabilized laser.

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The Er:ﬁber-based laser frequency comb is a technologically mature tool for precision metrology with beneﬁts of long-term reliability and relatively low cost. However, in some applications, such as direct frequency comb spectroscopy [1,2] and the calibration of high-precision astronomical spectrographs [3], it would be valuable to continuously extend the wavelength coverage of the Er:ﬁber-based laser frequency comb (LFC) below 1 μm and into the visible. Earlier efforts have accomplished this by making use of second harmonic generation and nonlinear broadening [4], off-resonant quasi-phase matched interactions in waveguides [5], or a combination of large mode-area ﬁbers and cascaded nonlinear ﬁbers [6]. Here, we present a technique for generating a visible light frequency comb from a mode-locked erbium laser that is self-referenced and frequency-stabilized using established techniques. In nonlinear ﬁber, we shift signiﬁcant pulse energy to the 1 μm region, where it is ampliﬁed with a core-pumped Yb:ﬁber ampliﬁer [7–11]. The ampliﬁer output is then compressed to provide a 73 fs pulse, which is spectrally broadened to below 650 nm using microstructured ﬁber. Signiﬁcantly, we verify that the coherence of the original Er: ﬁber source is transferred to the ampliﬁed 1040 nm pulses, and that, with subsequent nonlinear broadening, the multibranch system provides a coherent LFC with nearly two octaves of bandwidth from 660 nm to beyond 2100 nm.

Intense ultrashort pulses at 1.04 μm are generated from a 250 MHz mode-locked Er: ﬁber laser [12] using a series of ampliﬁers and nonlinear ﬁbers, shown in Fig. 1. One third (35 mW) of the light produced by the Er: ﬁber laser is ampliﬁed in a core-pumped Er: ﬁber ampliﬁer to an average power of 450 mW. Dispersion management and nonlinear pulse shortening are achieved by carefully trimming the length of standard anomalous-dispersion single-mode ﬁber (SMF) between the laser and the gain ﬁber, and by making use of a normal-dispersion Er:doped ﬁber [13] (nLight Er80 4/125). After recompressing the ampliﬁed pulses in SMF, a pulse duration of ∼70 fs at 1580 nm is achieved as measured using second harmonic generation frequency-resolved optical gating (SHG-FROG) [14].

The erbium ampliﬁer output is fusion spliced to a 5 cm piece of solid-core highly nonlinear ﬁber (HNLF) [15] with dispersion of 7.7 (ps/nm)/km at 1600 nm. This generates a supercontinuum with ∼8% of the 240 mW power coupled into the SMF falling between 1000 nm and 1100 nm. Within that range, the placement of the spectral peak can be reﬁned by tuning the polarization state of light entering the Er: ﬁber ampliﬁer and the HNLF. For example, to allow ampliﬁcation in Yb ﬁber at 1030 (1050) nm, the peak can be centered at 1027 (1065) nm, with 14 (11.5) mW of power in a 70 (100) nm bandwidth. The HNLF output is then spliced to an ∼50 cm length of SMF, which is in turn spliced to a core-pumped ytterbium ﬁber ampliﬁer that provides an ampliﬁed average power of 400 mW at a pump power of ∼1 W. For environmental stability, the entire fully-spliced ampliﬁer and HNLF apparatus is placed inside a small box.

Using a volume phase holographic single grating compressor [16], the ampliﬁed 1040 nm pulses are compressed with 75% power efﬁciency to 73 fs duration, as measured by SHG-FROG (Fig. 2). To generate a spectrum extending into the visible, these pulses are coupled into a 0.5 m microstructured nonlinear ﬁber with a zero-dispersion wavelength of 945 nm. Accounting for losses in the grating compressor and ﬁber coupling, about 110 mW of power was launched into the microstructured ﬁber. This generates an octave spanning spectrum from 660 nm to 1320 nm [Fig. 1(a)].

In order to verify that the light produced by the chain of ampliﬁers and nonlinear ﬁbers retains the coherence of the mode-locked laser, a series of heterodyne measurements were conducted. First, a second output from the mode-locked Er laser was used to generate an octave spanning spectrum from 1 μm to 2 μm, which enabled frequency detection of the carrier-envelope offset frequency (Δ̇νCE0) with a standard f−2f interferometer (free-running SNR of 35 dB in 300 kHz BW) and stabilization via feedback to the laser’s pump current. The laser repetition rate (νrep) was also stabilized relative to a Rubidium clock or hydrogen maser. Subsequently, utilizing the octave spanning spectrum from the microstructured
fiber, a second $f\cdot2f$ interferometer between 660 nm and 1320 nm was constructed to detect an out-of-loop copy of $f_{\text{CEO}}$ (free-running SNR of 25 dB in 300 kHz BW). We then used a high-resolution ($\Lambda$) frequency counter [17] to characterize the instability of the in-loop (1 $\mu$m to 2 $\mu$m) and out-of-loop $f_{\text{CEO}}$ beats. The Allan deviations computed from the time series of 1 s counter readings are shown in Fig. 3. As seen, the instability of the in-loop $f_{\text{CEO}}$ is counter limited near $2 \times 10^{-18}$ at 1 s of averaging time, while the instability of the out-of-loop $f_{\text{CEO}}$ is only 640 mHz deviation (fractionally $1.4 \times 10^{-15}$) at 1 s averaging time.

We also measured the phase noise of the two copies of $f_{\text{CEO}}$ (Fig. 4). Above Fourier frequencies of approximately 400 Hz, the two sets of data are nearly identical. Quantitatively, the integrated phase noise from 1 MHz to
1 Hz is seen to increase from 0.61 (in-loop) to 0.78 rad (out-of-loop.) At low frequency, the phase noise of the out-of-loop $f_{CEO}$ increases significantly, consistent with the counter data of Fig. 3, and is most likely a result of thermal and acoustic perturbations. Nonetheless, there is only a 20% increase in the integrated phase noise between the two $f_{CEO}$ beats, indicating minimal coherence degradation. This excess noise could be removed with a low-bandwidth servo [11].

Additional independent evidence of the good coherence of the broad bandwidth continuum is provided by measurement of a beat note between the visible comb light and a cavity-stabilized 657 nm CW laser [18] (linewidth ~1 Hz). A signal-to-noise ratio of $>25$ dB (300 kHz resolution bandwidth) was achieved [Fig. 1(b)] and the beat was measured using a frequency counter. The instability of this beat is shown in Fig. 4. When the mode-locked laser is referenced to a Rb microwave clock, the measured stability is consistent with the $2 \times 10^{-11}$ fractional stability of the Rb clock itself. Referencing the laser to the hydrogen maser reduces the short-term instability by more than an order of magnitude. At time scales of tens of seconds, both measurements show the long-term drift of the optical cavity to which the CW laser is stabilized.

In summary, we have demonstrated an all-fiber source of high-quality pulses at 1040 nm that are compressible to 73 fs. The short duration and high peak power of these pulses enable coherent and continuous extension of the Er-fiber-based frequency comb to visible wavelengths. We envision this source will be useful for broad-bandwidth spectroscopy and for generating, with filtering, a LFC-based calibration of high-precision astronomical spectrographs in the near-infrared and visible.

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