Optical frequency metrology using spectrally tailored continuum from a nonlinear fiber grating

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Abstract: We report the significant enhancement (~24 dB) of the optical beat note between a 657-nm CW laser and the tailored continuum generated with a nonlinear fiber Bragg grating. The same continuum is used to stabilize the offset frequency of a Cr:forsterite femtosecond laser.

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In the past several years, the technological maturity of ultrafast lasers as well as supercontinuum generation in nonlinear optical fibers has revolutionized optical frequency metrology [1-3]. Stabilized frequency combs have enabled the straight forward measurement of optical frequencies with unprecedented precision and the implementation of atomic clocks based on optical standards. One aspect of the frequency stabilization of a frequency comb is self-referencing, which often uses the octave-spanning supercontinuum from a nonlinear fiber to detect and stabilize the carrier-envelope offset frequency (f_0) [1]. Another aspect involves heterodyning specific modes of the comb with optical frequency references, hence, higher power at specific wavelengths in the supercontinuum is critical [3]. While some design elements of nonlinear fibers (i.e. choice of zero dispersion wavelength and fiber core diameter) provide coarse selection of the generated continuum, generally speaking there is very little user control over the output spectrum. To make the matter more difficult, the continuum is rarely uniform, but rather contains spectral regions with very little light. Thus, several fibers must typically be tested in order to find one that reliably generates an octave of spectrum plus significant light at the desired wavelengths. Clearly, technologies that permit designed spectral enhancement on top of an octave-spanning supercontinuum would be very beneficial for optical frequency metrology.

Here we demonstrate the use of tailored spectra from a nonlinear optical fiber that allow the robust generation of continuum at the specific wavelength important for experiments with the Ca optical frequency standard. We measure a significant increase (~24 dB) in the signal-to-noise of optical beat notes between a stable CW laser at 657 nm and the second harmonic of the continuum generated by a Cr:forsterite femtosecond laser that is coupled into a highly nonlinear fiber (HNLF) containing a Bragg grating designed to enhance the region around 1314 nm. At the same time, the HNLF generates an octave of continuum that permits the measurement and control of f_0.

The supercontinuum is generated with 1.2-nJ, 35-fs pulses centered at 1.26 μm from a 433-MHz Cr:forsterite laser [4] that are injected into a ~2-m long piece of dispersion-flattened highly nonlinear optical fiber (HNLF) containing a fiber Bragg grating (i.e. a resonant structure with periodic modulations of the core refractive index) [5, 6]. The grating was inscribed in HNLF by scanning a ~1 cm Gaussian beam (248 nm pulsed) over 24.5 mm of fiber at uniform velocity through a phase mask[6]. Spectral enhancement of >10dB has been observed with UV-inscribed fiber Bragg gratings at 990, 1080, and 1480 nm [6]. However, large temporal broadening and the dispersion change due to the fiber grating made it unclear if an octave spanning supercontinuum could be obtained along with significant spectral enhancement after frequency-doubling [7].

A portion of the octave-spanning continuum from 1.0 μm to 2.2 μm previously generated from HNLF that did not contain a grating is shown in Fig. 1(a) [8]. A significant spectral enhancement (~20 dB) at 1314 nm is observed with the same HNLF that contains a fiber grating, as also shown in Fig. 1(a). (Similar enhancement is also observed by injecting femtosecond 1.55-μm pulses from Er-doped fiber mode-locked laser.) The f_0 beat, as shown in Fig. 1(b), is detected using the conventional f-to-$2f$ self-referencing technique. To do so, the 2040-nm light is frequency-doubled by a $KNbO_3$ crystal and combined with the fundamental light at 1020 nm. The S/N ratio of f_0 beat is >27 dB at 100 kHz resolution bandwidth (RBW), which is sufficient for stabilization of f_0. We frequency-doubled the spectral components of the supercontinua near 1314 nm from the HNLFs with and without a grating in periodically-poled Lithium Niobate (PPLN), and heterodyned them with the CW light from a stabilized laser diode at 657 nm (linewidth ~10 Hz). Figure 1(c) is the second-harmonic generation (SHG) spectra after PPLN and ~24 dB enhancement is observed. Accordingly, those beat signals with a stabilized CW light at 657 nm also show ~24 dB enhancement as seen in Fig. 1(d) and (e).

These results should lead to improved stabilization of the Cr:forsterite laser relative to the 657 nm Ca standard (a tracking oscillator was previously required for the beat at 657 nm [8]). Thus stabilized, it will be valuable to investigate the noise properties of the Cr:forsterite frequency comb with the goal of using it as a means of transmitting microwave and/or optical frequency standards via fiber optic networks[9].

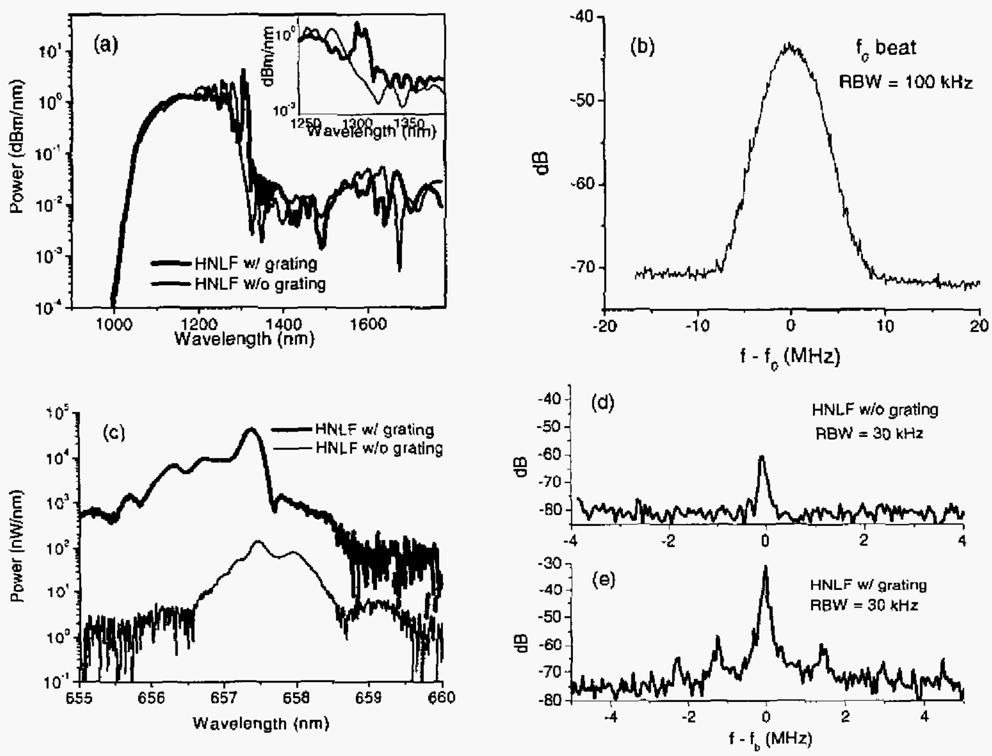

Fig. 1. (a) Supercontinua generated using a HNLF with and without a grating. The inset graph is the zoomed spectra around 1314 nm region. (b) f_0 beat note with HNLF. S/N ratio is >27 dB at 100 kHz RBW. (c) SHG powers after frequency doubling of spectral components at 1314 nm using PPLN after a HNLF with and without grating. Beat notes observed between a CW laser at 657 nm and the frequency-doubled comb elements after a HNLF (d) without grating (S/N~20.5 dB) and (e) with grating (S/N~44.5 dB) at 30 kHz RBW.

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