Multi-branch Fiber Frequency Comb for Precision Frequency Measurement of Molecular Transitions

Mingkun Li[1,2], Pan Zhang[1,2], Bingjie Rao[1], Lulu Yan[1], Yanyan Zhang[1,*], Haifeng Jiang[3], Shougang Zhang[1,2]

[1] Key Laboratory of Time and Frequency Primary Standards, National Time Service Center, Chinese Academy of Sciences, Xi'an, China

[2] School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing, China

[3] Shanghai Branch, National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Shanghai, China

* zhangyanyan@ntsc.ac.cn

***Summary*—Precision spectrum measurement is one of the main applications of optical frequency combs. In this paper, we demonstrate a multi-branch optical frequency comb based on an erbium-doped-fiber femtosecond laser with a polarization-maintaining '9' cavity. The comb includes five output ports with the target wavelengths including 1083 nm, 1380 nm, 1637 nm, 1064 nm and 1750 nm. The in-loop stabilities of the repetition rate and carrier-envelope-offset frequency are 2.9×10^{-13} and 1.7×10^{-18} at 1 second integration time respectively, which meets the sub-kilo hertz cavity ring-down spectroscopy (CRDS) measurements requirements.**

***Keywords*—optical frequency comb, nonlinear amplifying loop mirror, precision frequency measurement**

I. Introduction

Optical frequency comb is a frequency-controlled mode-locked laser. In the frequency domain, it is a set of single frequency signal with strictly equal frequency intervals. Due to this frequency characteristic, optical frequency combs are usually used as the tool of frequency transmission and precision frequency measurement in many research fields and has brought a series of breakthroughs [1,2]. As an important application of optical frequency comb, precision molecular spectroscopy are conducive for the understanding of quantum physics. In recent researches, scientists combined frequency combs and the cavity ring-down spectroscopy (CRDS) to detect molecular rotational-resolved transitions and has reduced the fractional uncertainties to 10^{-12} level [3-5]. These systems are extensible for many molecular transition measurements with different transition frequencies. However, traditional optical frequency comb cannot meet the measurement requirements for all these frequencies [4,6-8]. Therefor a new kind of optical frequency comb which can be used for frequency measurement at multiple frequencies must be developed.

In this paper, we demonstrate an Er: fiber frequency comb with customized five branches, enabling sub-kilo hertz CRDS measurements at 1083 nm, 1380 nm, 1637 nm, 1064 nm and 1750 nm, which can be applied in the precision frequency measurement of a series of molecular transitions.

II. Experiment setup

The schematic of the frequency comb is shown in Fig. 1. It consists the femtosecond laser, the detection and control unit of f_{ceo} and f_{rep}, and the application branches.

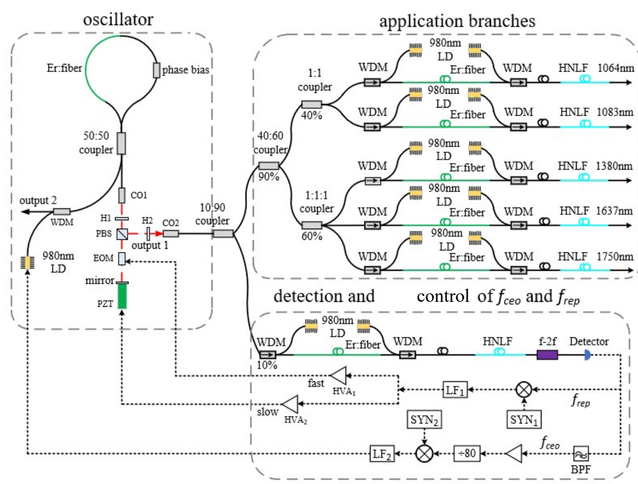

Fig. 1. Schematic of the Er:fiber frequency comb. LD: laser diode; PZT: piezoelectric transducer; EOM: electro-optic modulator; PBS: polarization beam splitter; H: half-wave plate; CO: collimator; WDM: wavelength division multiplexer; HNLF: highly nonlinear fiber; *f-2f*: *f-2f* interferometer; BPF: band-pass filter; LF: loop filter; SYN: synthesizer; HVA: high voltage amplifier.

The laser is an erbium-doped-fiber femtosecond laser based on nonlinear amplifying loop mirror (NALM) mechanism, fabricated with all polarization-maintaining (PM) components to enhance the robustness and reduce the frequency instability. It is composed of a 980 nm laser diode as the pump, a linear cavity in free space and a PM fiber cavity. The net dispersion of the cavity is about −0.007 ps^2. A piezoelectric transducer (PZT) and an electro-optic modulator (EOM) are used for slow and fast control of repetition frequency respectively. Two half-wave plates are inserted to adjust the output power (H1) and the polarization state (H2) of output1. The output power of output1 and output2 is 10 mW which is distributed by a 10:90 coupler with 1 mW for f_{ceo} detection and 9 mW for the application branches, The output power of output2 is 6 mW, used for monitoring the operation state of the oscillator.

The f_{ceo} detection portion includes a PM erbium-doped amplifier (EDFA), a PM highly nonlinear fiber (HNLF), an integrated f-$2f$ interferometer and a photodetector. First, pulses are amplified by chirped pulse amplification. Then the amplified pulses are compressed to 65 fs by a PM1550 fiber. High power ultrashort pulses stimulate the nonlinear effects in the HNLF, making an octave-spanning supercontinuum, to obtained f_{ceo} from f-$2f$ interferometer. After that, f_{ceo} and f_{rep} are entered into the phase-locked loop, and stabilized by controlling the injection current of the 980 nm pump LD of the oscillator and the operating voltage of the EOM and PZT.

The comb has five application branches for CRDS measurement, two branches (1064 nm and 1083 nm) for the stabilization of the reference laser and the probe laser, others (1380 nm, 1600 nm and 1750 nm) for phase locking of the extended cavity diode laser (ECDL). The compositions of these application ports are similar to the f_{ceo} detection portion, except no f-$2f$ after the HNLF. Here, we use a PM-HNLF with the ZDW of 1405 nm for the 1064 nm, 1083 nm and 1637 nm ports, a HNLF with the ZDW of 1350 nm for the 1750 nm port and a HNLF with the ZDW of 1525 nm for the 1380 nm port.

III. Results and Discussion

In the experiment, the initiation of mode locking is easily achieved when pump power over 1 W. The repetition frequency of the laser is 136 MHz. The output spectrum of output1 and output2 at the pump power of 450 mW is shown in Fig. 2(a) and 2(b). The full width at half-maximum (FWHM) of output1 is about 30 nm, deriving the Fourier transform-limited pulse duration as 88 fs.

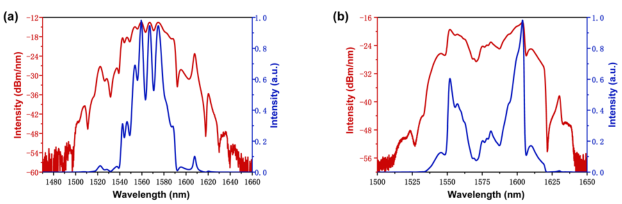

Fig. 2. Spectra in linear (blue) and log (red) scales from output1 (a) and output2 (b).

Fig. 3(a) is the radio frequency (RF) spectra of f_{ceo} and f_{rep} with 300 kHz resolution bandwidth (RBW). The signal-to-noise ratio (SNR) of f_{ceo} is 35 dB, adequately high for the phase locking. Here, the signal of f_{ceo} around 230 MHz is selected and divided by 80 to be phase locked to a 2.875 MHz reference (Model SG382).

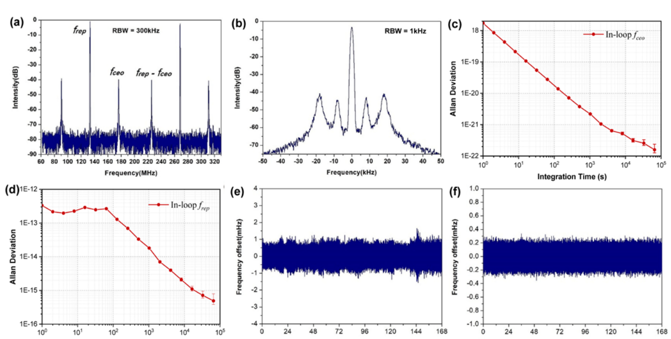

Fig. 3. (a) radio frequency spectra of f_{ceo} and f_{rep}. (b) Spectrum of the frequency-divided in-loop f_{ceo}. (c) In-loop relative frequency stability of f_{ceo} (solid red square). (d) In-loop relative frequency stability of f_{rep}. (solid black square) and the floor of the measurement system (solid red circle). (e) Recorded frequency offset of phase-locked f_{ceo}. (f) Recorded frequency offset of phase-locked f_{rep}.

Fig. 3(b) shows the spectrum of the phase-locked frequency-divided in-loop f_{ceo} with 1 kHz RBW. The control bandwidth of the loop is about 20 kHz. Fig. 3(c) indicates the in-loop relative frequency stability of f_{ceo} (normalized with the optical frequency of 193 THz), which is 1.73×10^{-18} at 1 second and rolls down to 10^{-22} level at 10^4 second with the slope of $1/\sqrt{\tau}$. Meanwhile, the f_{rep} is phase locked to a 136 MHz reference. Fig. 3(d) shows the in-loop relative frequency stability of f_{rep} (normalized with the radio frequency of 136 MHz), which is about 2.88×10^{-13} at 1 second and rolls down to 10^{-15} level at 10^4 second. Fig. 3(e) and 3(f) present the recorded frequency offset of phase-locked f_{ceo} and f_{rep} as a function of time. The standard deviations for f_{ceo} and f_{rep} are estimated to be 273 μHz and 67 μHz respectively.

Fig. 4(a) to 4(e) show the spectra of the five application ports with target wavelengths of 1064 nm, 1083 nm, 1380 nm, 1637 nm and 1750 nm respectively. We estimated the single mode energy at the target wavelength. The energy at 1064 nm, 1083 nm, 1380 nm, 1637 nm and 1750 nm is about 220 nW/mode, 370 nW/mode, 630 nW/mode, 320 nW/mode and 730 nW/mode. Fig. 4(f) shows an example of the detected beat signal, which was obtained between a 1060-nm narrow linewidth laser and the 1064-nm port of the comb. The SNR of all the beat note is over 30 dB, which is sufficient for frequency stabilization.

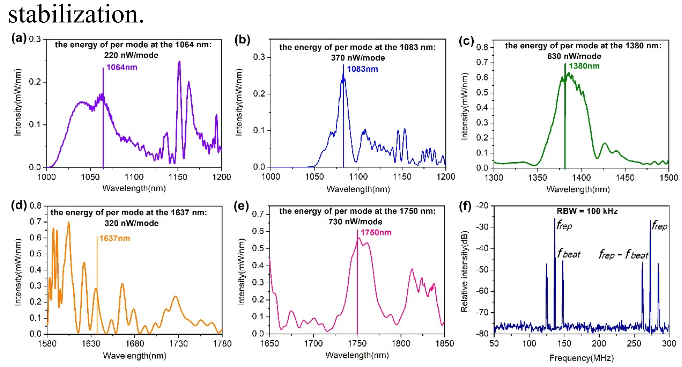

Fig. 4. Supercontinuum (SC) spectrum of the 1064 nm (a), 1083 nm (b), 1380 nm 1637 nm (d) and 1750 nm (e) application ports. (f) The frequency spectrum of the beat-note between the 1064 nm application port and a narrow linewidth lasers with 100 kHz RBW.

IV. Conclusions

In conclusion, we have demonstrated a polarization-maintaining Er: fiber frequency comb, based on a nonlinear amplifying loop mirror, with five application branches for precision frequency measurement of atomic/molecular transitions in the near-infrared region. We have confirmed that the frequency comb are proper functioning during the long-term operation. This kind of polarization-maintaining Er: fiber frequency comb with multi-application branches It can be used not only for CRDS measurement, but also for many applications such as frequency comb spectroscopy and lattice clocks.

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