Supplementary Material

Random fiber laser using a cascaded fiber loop mirror

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Section A. Laser characteristics with 10-CFLM.

Figure S1a shows the exponential decay of spatial intensity distribution at λ_1 with a linear fitting. The light has an intensity of less than -10 dB before the 10th FLM and thus is trapped in the 10-CFLM. The light with such intensity distribution would eventually show localized distribution and demonstrate the Anderson localization.[39]

We used the delayed self-heterodyne technique to measure the linewidth of the RFL. A 50-km delay fiber and an acousto-optic frequency shifter of about 192 MHz were placed on the two arms of the Mach-Zehnder interferometer, respectively. The heterodyne signal was measured by a photodetector and an electrical spectrum analyzer. Figure S1b shows the measured result under the pump power of 22 mW. The fitted Lorenz curve has a 20 dB linewidth of 79.7 kHz, which yields a 3 dB linewidth of about 4 kHz of the laser.[26] The linewidth of the laser increases to about 7.4 kHz under the maximum pump power because of the increasing number of lasing modes. Moreover, the linewidth increases with the decrease of the number of FLM, and reaches 5.4 kHz with one FLM under the pump power of 22 mW. This is because more FLMs could have a stronger filter effect on the intracavity modes.
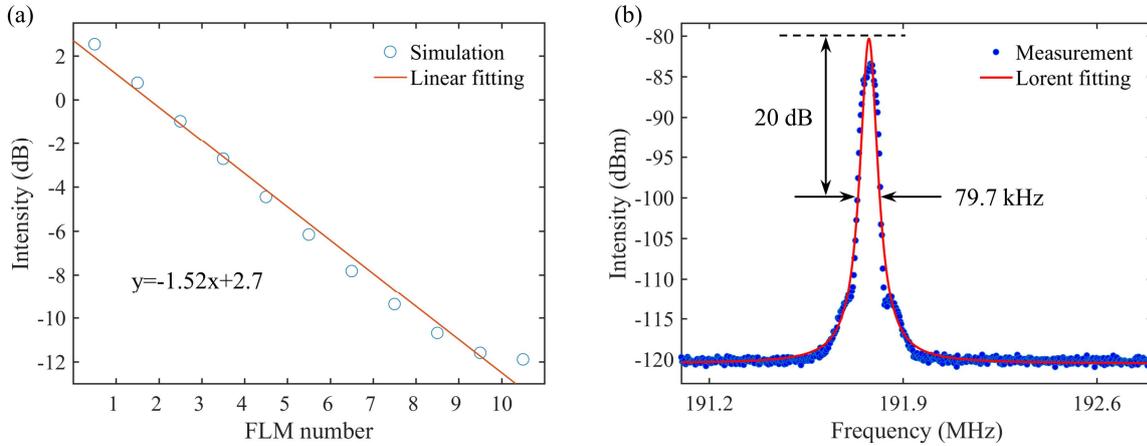

Figure S1. (a) Spatial intensity distribution at λ_1 of the 10-CFLM and the linear fitting. (b) Delayed self-heterodyne result under the pump power of 22 mW.

The output of the RFL was detected by a 40-GHz AC-coupled photodiode and an oscilloscope (LabMaster 10-36Zi-A, LeCroy) with 80 GHz sampling rate. Different conditions like continuous and self-pulsing are shown in Fig. S2a. We applied the Fast Fourier Transform (FFT) to the time series and obtained the corresponding frequency results in Fig. S2b. The laser in continuous operation shows no beat peaks, but obvious peaks appear when the self-pulsing happens. The beat peaks are due to the F-P cavities formed by the FLMs and they differ from

each other in each measurement. The high sensitivity of the CFLM and the complex mode competition and mode hopping in EDF results in the diverse time-domain performance. The relatively high erbium concentration and low output coupling ratio in our proposed laser is also conducive to the formation of self-pulsing.[51] The generated pulses enhance the interference effect in the FLM, which can be treated as a nonlinear optical loop mirror with saturable absorption effect. [52] Then the pulsing condition is reinforced and causes the time-varying results shown in Fig. S2. Figure S2c shows two single-measured radio frequency spectra with some different beat peaks.
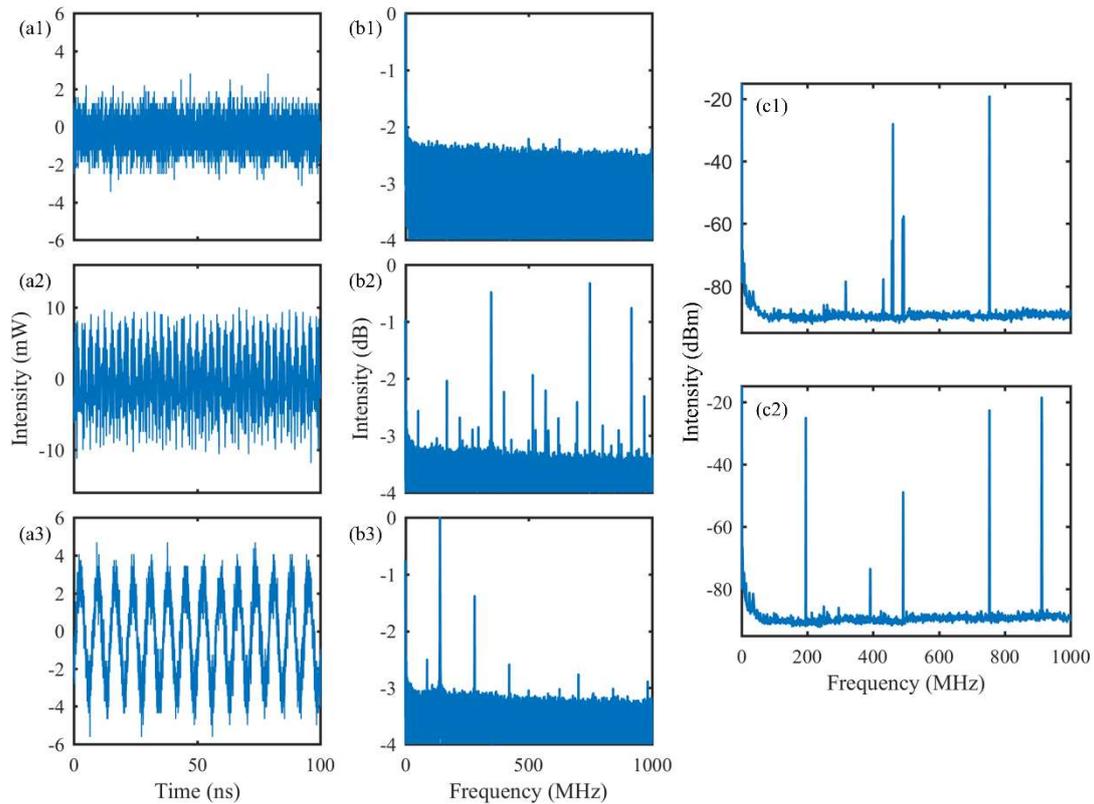

Figure S2. (a) Time series and (b) corresponding FFT results. (c) Single-measured radio frequency spectra at two times.

Section B. Laser characteristics with 3-CFLM.

The 3-CFLM is still of high regularity and the FSR of the reflection spectrum is quite small (~1 pm), as shown in Fig. S3. Compared with the 10-CFLM, more longitudinal modes can start to oscillate in the FWHM of the used FBG. Therefore, the laser operates in a traditional laser mode and the cavity length is quasi-fixed.
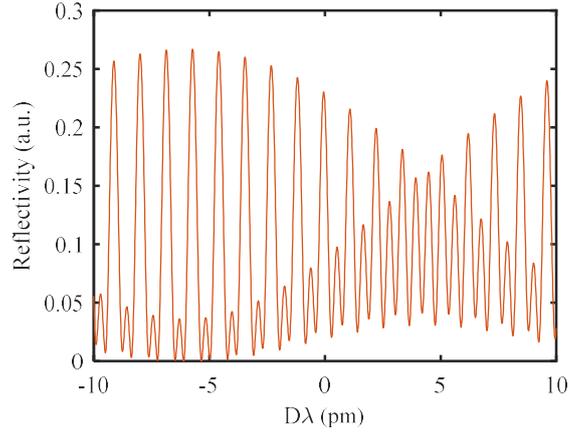
Figure S3. Simulated reflection spectra of the 3-CFLM at 1550 nm.

Different from the Fig. S2a, the times series in Fig. S4a exhibit a constant self-pulsing condition, which means the increasing number of FLM may be conducive to the suppression of self-pulsing effect and lead to a more stable output. The FFT results in Fig. S4b show the highest peak at 128.7 MHz surrounded by some lower peaks corresponding to the beat peak at 7.74 MHz. The 7.74 MHz corresponds to a time interval of 129 ns, which is consistent with the large envelope of pulses in Fig. S4a2. Figure S4c shows two single-measured radio frequency spectra at two times, which are different from the averaged results in Fig. 7a2. The newly appeared peaks in each measurement are caused by the time-varying lasing modes in the random fiber laser and are recorded by the averaged measurement operation.
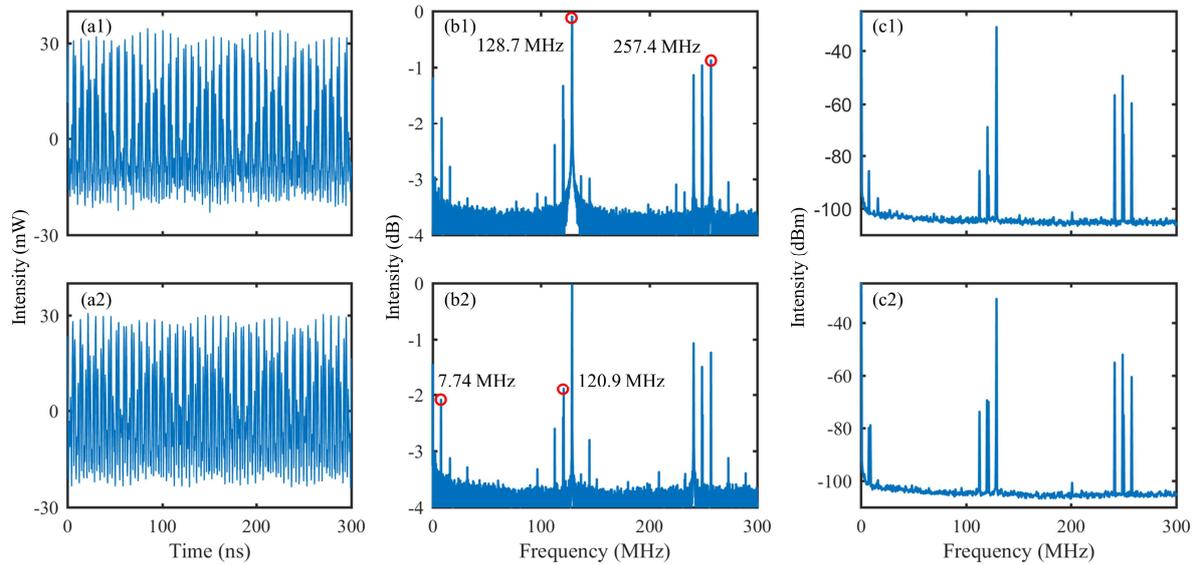

Figure S4. (a) Time series and (b) corresponding FFT results. (c) Single-measured radio frequency spectra at two times.

The lower peaks are the results of the beat between the two adjacent F-P cavities formed by FLM_1-FLM_2, and FLM_2-FLM_3, respectively. The cavity length difference ΔL can be calculated

by:

$$\Delta L = \frac{c}{nRF_1} - \frac{c}{nRF_2} \qquad (1)$$

where $c = 3\times10^8$ m s^{-1} is the speed of light, $n = 1.45$ is the refractive index, $RF_1 = 120.9$ MHz and $RF_2 = 128.7$ MHz are beat peak frequencies (as shown in Fig. S4b). The calculated ΔL, 0.1 m, is almost equal to the measured result, 0.08 m. The difference should be caused by the experimental measurement error.

To further test the explanation for the beat peaks, we fabricated another 3-CFLM with the same fiber length and measured the radio frequency spectrum. The result is shown in Fig. S5 and the beat peaks are circle-marked. New peaks also appear between each measurement. A small fiber length difference could cause the shift of the beat peaks, but the calculated ΔL is still 0.1 m. The low peak at 8.8 MHz equals to the difference between two peaks (140.5-131.7 MHz).
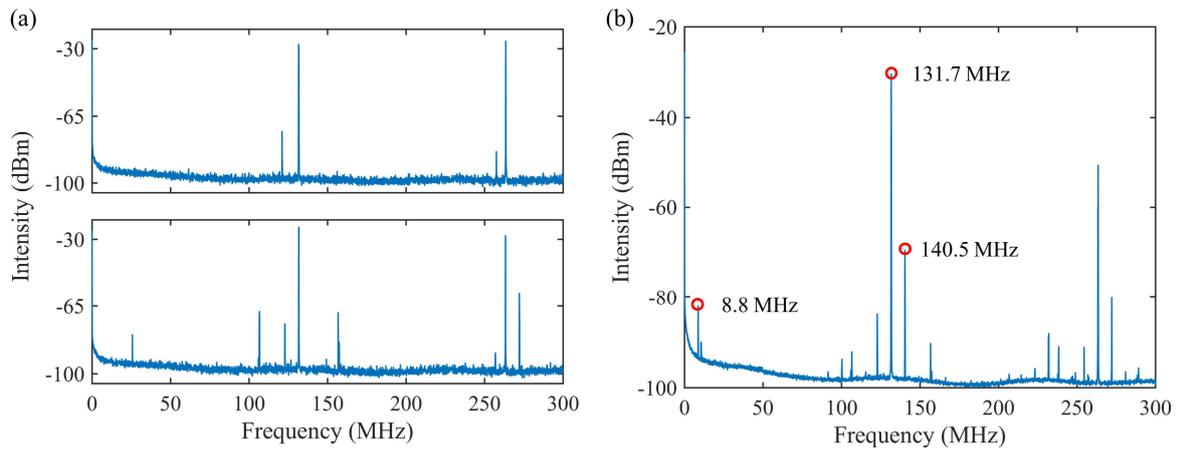

Figure S5. Radio frequency spectrum with another 3-CFLM. (a) Single-measured at two times. (b) Averaged by 20 measurements.