Mitigation of the supermode noise in a harmonically mode-locked ring fiber laser using optical injection: supplement

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This Supplementary Material gives details on the experimental setup adjustment. It also provides additional experimental data on the effects observed in an extended spectral range of the harmonically mode-locked laser operation and involving Kelly sidebands of different orders.

Setup adjustment procedure. The experimental setup is shown in Fig.1. To demonstrate the effect, the setup adjustment procedure to be applied is the following:

Step 1. Identification of the FTM bands. Switch off the HML laser pump power. Switch on the tunable CW laser. Set the CW laser power at 3.5 mW. Adjust PC3 to maximize the CW laser power injected into the HML laser cavity. Use a photodetector attached to the HML laser output for this purpose. Scan the CW laser wavelength over the whole spectrum range recording the light intensity at the HML laser output as a function of the CW laser wavelength. Identify the maximal points of the birefringent fiber filter transmission spectrum and mark the FTM bands (~1nm) similar to those shown in Fig.S1 (gray areas). Note that the FTM band does not change until the birefringence of the HML cavity fiber changes.

Step 2. Adjustment of PC2. PC2 is used to control the polarization state of the injected light. Set the CW laser wavelength to be within one of the FTM bands. Adjust PC2 to get the maximal power of the injected light detected at the HML laser output and keep the settings fixed. Importantly, in the case of any manipulations with the laser causing a change of the cavity fiber birefringence, Step 1 and Step 2 should be repeated.

Step 3. Setting the HML laser operation. Switch off the tunable CW laser. Switch on the HML laser and set the pump power to any desired level above the laser threshold. Use the optical spectrum analyzer and RF spectrum analyzer to monitor laser operation regime. Using a rough

Fig. S1. Optical spectra recorded with HML laser operating at different wavelength but the same PRR of 517 MHz. The fiber birefringence filter transmission maximum (FTM) bands are marked (gray). The CW light wavelength coincides with the FTM band in all cases.
adjustment of PC1 tune the HML laser operation wavelength to the desired spectrum range selected from a few spectral bands between 1550 and 1590 nm specific for the built fiber configuration. Tune PC1 to shift the HML laser optical spectrum as a whole so that the Kelly sideband (nearest to the HML laser wavelength) coincide with one of the narrow FTM bands identified at Step 1. Then using delicate tuning of PC1 you can change the PRR while keeping the Kelly sideband within the FTM band. An increase or decrease of the PRR occurs by discrete steps within the range determined by the pump power level.

Step 4. Observation of the effect. Turn on the tunable CW laser. Set the CW laser power at 3.5 mW. Using PC3 maximize the injected light power. Turn the CW laser wavelength towards the Kelly sideband (coinciding with the FTM band). Once the CW laser wavelength gets the Kelly sideband, the optical HML laser spectrum monitored with the optical spectrum analyzer undergoes a shift and the SLL monitored with the RF spectrum analyzer gets an increase. The attached video visualizes this process.

Observation of the effect with different Kelly sideband orders. The effect has been observed in an extended range of the HML laser operation and with the CW light wavelength coinciding with the Kelly sidebands of different orders (up to the third-order). However, with the second- and third-order Kelly sidebands the effect is less pronounced. Figure S1 shows the laser optical spectra recorded at the PRR of 517 MHz with extended PC1 adjustment. The soliton HML laser spectra exhibit a weak asymmetry due to the fiber birefringence filter possessing different transmission at the left and right Kelly sideband frequencies [S1]. Specific features of Er-doped fiber gain spectrum could cause a similar effect [S2]. In the HML laser dynamics based on the NPE mechanism the fiber birefringence filter plays a crucial role. The spectral transmittance peaks of the filter are spaced periodically and for the considered laser implementation are centered around the wavelengths \( \lambda \approx 1544 \text{ nm}, 1555 \text{ nm}, 1566 \text{ nm}, 1577 \text{ nm} \). The marked band in Fig.S1 shows narrow (< 1 nm) FTM bands centered at these wavelengths. One can see that the recorded laser optical spectra exhibit the same periodicity. The effect of supermode noise reduction is described in our Letters when the first-order Kelly sidebands are fixed within one of the FTM bands and CW light is injected into this Kelly sideband. We have found that it should not necessarily be the first-order Kelly sidebands. Indeed, the first-order Kelly sidebands provide both the maximal increase of the SSL (~30 dB, spectra # 3, 4, 5) and the maximal wavelength shift of \( \Delta \lambda = 0.7 \pm 1 \text{ nm} \). However, a less pronounced effect is possible with the second- (#1) or third-order (#2) Kelly sidebands. To get the effect one of these Kelly sidebands should coincide with one of the FTM band. Then the injection of the CW light into the selected Kelly sideband causes an increase of the SSL by ~25 dB for #1 and ~20 dB for #2 accompanied by the optical spectrum frequency shift by ~0.5 nm for #1 and ~0.3 nm for #2.

Media. A supplemental video file describes modifications of the optical spectrum (Media S1) induced by the CW light injection. The CW light wavelength is scanned over the spectrum approaching the Kelly sideband properly fixed within the FTM band in advance. Once the CW wavelength gets the Kelly sideband, the top of optical spectrum is shifted towards the CW line.

REFERENCES: