

A PHASE LOCKED FREQUENCY COMB FROM AN ALL-FIBRE SUPERCONTINUUM SOURCE

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Abstract A phase-locked, frequency comb in the near-infrared is presented. Self-referencing detection and stabilization of the carrier-envelope-offset frequency is demonstrated in an all-fibre supercontinuum source, based on an amplified, modelocked erbium-fibre laser and highly-nonlinear, dispersion-shifted fibre.

Introduction

Stabilized frequency combs have revolutionized frequency metrology and optical clocks¹⁻³. The output of a modelocked pulse train forms a comb of frequencies, with the spacing of the comb set by the repetition rate of the laser, f_r , and the offset of the comb determined by the carrier-envelope-offset (CEO) frequency, f_0 . To create a stabilized optical comb, both degrees of freedom must be controlled. The ability to generate an octave of bandwidth with supercontinuum generation in microstructured fibres has allowed for the self-referencing detection of f_0 and stabilization of both degrees of freedom of the optical comb.

To date, all demonstrations of self-referenced, stabilized laser systems have used modelocked, bulk solid-state lasers as the pulse source and covered the frequency range from 400-1100nm. However, a fibre laser based system holds a number of potential advantages over bulk optic lasers in terms of size, cost, efficiency, and optical alignment. Furthermore, it is advantageous to extend coverage of precision optical combs into the near infrared region to take advantage of the low-loss window of optical fibres and fibre based components.

Recent results have shown that an all-fibre system is capable of generating an octave-spanning continuum⁴, and this continuum can be used to detect the CEO frequency⁵. In this work, we demonstrate the first, fully phase-locked, self-referenced frequency comb from a fibre laser based system. The optical comb spans the range from 1100 nm to greater than 2200 nm.

All-fibre supercontinuum source

A diagram of the experimental setup is shown in Fig. 1. A passively modelocked, erbium-doped fibre laser supplies pulses with ~ 50 MHz repetition rate, a bandwidth of ~ 20 nm, and an average power of 2 mW. These pulses are amplified and compressed in an erbium-doped fibre amplifier. The pulses at the amplifier output have an average power of ~ 100 mW and a FWHM of < 70 fs. A length of dispersion

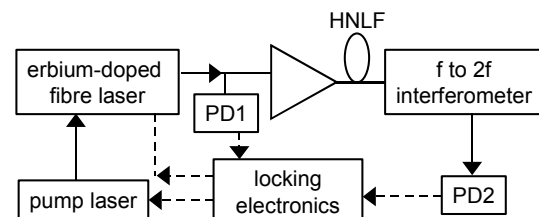


Fig. 1: Schematic of the experimental setup. Solid lines denote optical paths, and dashed lines denote electrical paths.

flattened, highly-nonlinear, dispersion-shifted fibre (HNLF) is spliced directly to the amplifier output. It should be noted that this setup is in contrast to the setup in Ref. 5 where bulk optics were used to recompress the pulses after the amplifier and focus into the nonlinear fibre. The ability to splice the HNLF directly to the amplifier output eliminates alignment concerns due to focusing into small core nonlinear fibres and is a significant advantage of fibre based systems.

The highly-nonlinear, dispersion shifted fibre is similar to that used in Ref. 4, but with the design enhanced to flatten the dispersion slope to 0.009 ps/nm²-km. The dispersion at 1550 nm was 1.74 ps/nm-km and the nonlinearity was $\gamma \sim 10.6$ W⁻¹km⁻¹. An example of the continuum generated at the output of a 23 cm length

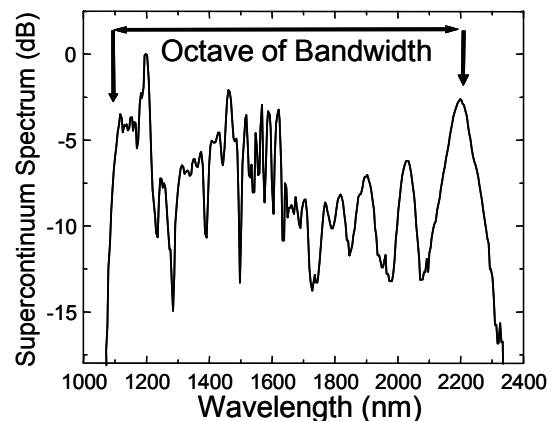


Fig. 2: Supercontinuum generated in 23 cm of dispersion flattened, HNLF.

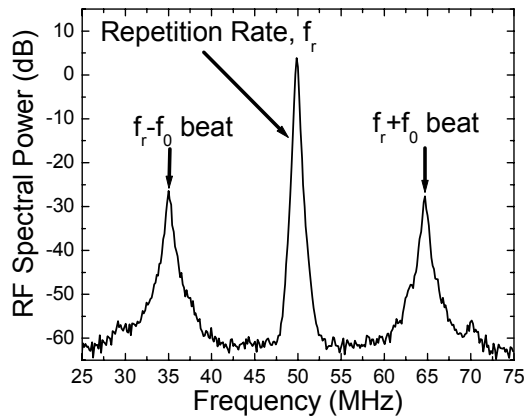


Fig. 3: RF power spectrum resulting from mixing the frequency doubled 2200 nm light with the 1100 nm fundamental light in the f to $2f$ interferometer. Both the repetition rate at 49.8 MHz and the f_0 beat note are clearly observed.

of HNLF is shown in Fig. 2. The continuum spans more than an octave, from 1100 nm to greater than 2200 nm.

Self-referencing CEO beat frequency detection and laser stabilization

The ability to generate an octave of spectrum does not guarantee the detection of the f_0 beat note. The use of very short lengths of HNLF and sub 100 fs pulses, both in this work as well as in the Ref. 5, help to minimize the noise associated with broadband supercontinuum generation⁶.

The continuum from the HNLF was sent to a standard f to $2f$ interferometer². Light at 2200 nm was frequency doubled in a type-I phase matched, 1mm thick LiIO₃ crystal. The frequency doubled 2200 nm light was recombined with the 1100 nm fundamental, sent through single mode fibre to ensure spatial overlap, and then detected with a 125 MHz InGaAs photoreceiver, PD2 in Fig. 1. The measured RF power spectrum from the photoreceiver is shown in Fig. 3. Both the repetition rate of the laser, at 49.8 MHz, and the f_0 beat note are clearly observed.

To create a phase-locked optical comb, both the repetition rate of the laser and the CEO frequency must be locked to a stable RF source. To lock the repetition rate, f_r , it was first measured with PD1, shown in Fig. 1. This signal was mixed with an RF synthesizer to create an error signal, which was fed back to a PZT based fibre stretcher that was included in the fibre laser cavity. The phase-locked repetition rate was counted with a 1 s gate time, giving a counter-limited standard deviation of 0.22 mHz, as shown in Fig. 3.

It has been shown previously that adjusting the pump power to the passively modelocked fibre laser changes primarily the CEO beat frequency⁷. The

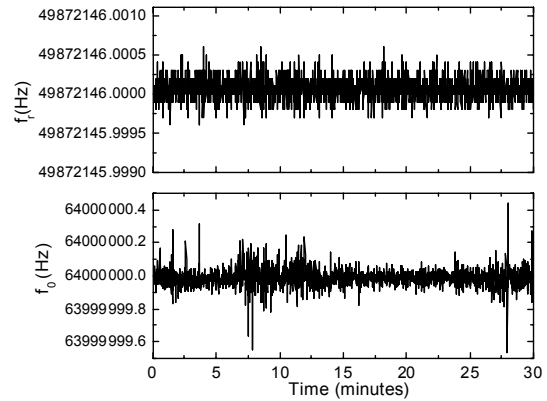


Fig. 4: Frequency counter results for the locked repetition rate (f_r) and CEO beat frequency (f_0) over 30 minutes. The standard deviation of the repetition rate is 0.22 mHz, which is the resolution limit of the frequency counter. The standard deviation of the CEO beat is 57 mHz.

repetition rate of the laser is also changed by adjusting the pump power, but this change is a factor 5×10^6 smaller than the f_0 change. Therefore adjusting the drive current of the fibre laser pump provides a means to stabilize f_0 . The phase locked beat signal is shown in Fig. 4; the counted f_0 for a 1 s gate time has standard deviation of only 57 mHz.

One significant technical issue with stabilizing f_0 is that relaxation oscillations in the fibre laser limited the bandwidth of the f_0 feedback control to ~ 5 kHz, although the FWHM of the f_0 signal is significant at 600 kHz. Therefore to achieve phase lock, the signal was divided down by a large factor before comparing with an RF reference to derive an error signal that drove the pump diode drive current.

Conclusions

We have demonstrated for the first time a fully phase-locked optical comb in the near infrared, generated from an all-fibre supercontinuum source. The phase-locked fibre laser system exhibits a stability comparable to the first Ti:Sapphire microstructured fibre systems. At the same time, a fibre based system offers a number of advantages in size and efficiency, and potential freedom from optical alignments.

References

- 1 T. Udem et. al., Nature **416** (2002) p. 233
- 2 D.J. Jones et. al. Science **288** (2000) p. 635
- 3 S.A. Diddams et. al. Science **293** (2001) p. 825
- 4 J.W. Nicholson et. al. Opt. Lett. **28** (2003) p. 643
- 5 F. Tauser et. al. Opt. Ex. **11** (2003) p. 594
- 6 K.L. Corwin, et. al. Phys. Rev. Lett. **90** (2003) p. 113904
- 7 J. Rauschenberger et. al. Opt. Ex. **10** (2002) p. 1404