Significant Carrier Envelope Offset Frequency Linewidth Narrowing in a Prism-based Cr:forsterite Frequency Comb

Karl A. Tillman, Rajesh Thapa, Brian R. Washburn and Kristan L. Corwin
Department of Physics, Kansas State University, Manhattan, KS 66506, U.S.A
tillman@phys.ksu.edu

Abstract: We report a dramatic reduction in the linewidth of the carrier envelope offset frequency of a frequency comb generated by a femtosecond prism-based Cr:forsterite laser due to changes in the wavelength-dependent intracavity loss.

OCIS codes: 120.3930 (Metrological instrumentation), 140.3580 (Lasers, solid state), 320.7090 (Ultrafast lasers)

1. Introduction

Optical frequency combs are a very precise way to measure optical frequencies with respect to RF or optical references. These frequency combs have two free parameters: the laser repetition rate (f_r) and the carrier envelope offset frequency (f_0). Often, f_0 is detected using a "self-referencing" technique [1] and the width of this signal reflects a measure of that stability. Although the most stable frequency combs have been obtained with Ti:sapphire lasers, optical wavelengths in the near infrared are more conveniently measured using near IR laser based combs. Fiber lasers have reached stabilities approaching that of Ti:sapphire, but are more limited in their maximum repetition rate. Cr:forsterite is the only near-IR solid-state laser to be stabilized using the "self referencing" technique, but the resulting f_0 beat was unexpectedly wide: 6 MHz as measured in Kim *et al's* chirped mirror based system [2] and 1.5 MHz in our prism-based system [3]. Both these lasers were pumped with a multi-mode Yb:fiber laser, thought to contribute significantly to the f_0 linewidth. We have recently narrowed the f_0 linewidth of our frequency comb by at least two orders of magnitude simply by inserting a knife edge into the laser cavity after the prisms for the purpose of wavelength-tuning the output.

Many studies have been made in Ti:sapphire [4,5] and Er:fiber lasers [6] to understand the dependence of f_0 on pump power (df_0/dP). Indeed the pump power is often used to servo-control the f_0 frequency. Prism-based lasers are known to exhibit both larger and smaller df_0/dP depending on slight changes to intracavity dispersion [4]. The f_0 linewidth (Δf_0) depends on pump power noise [6] and the frequency response rate of the laser [5]. If laser amplitude spectral noise density, $S_\nu(f)$, is white in frequency with units of dBc / Hz, then the key parameters that control Δf_0 are the frequency response of df_0/dP (as set by the gain medium and the laser cavity [6]) and frequency response roll-off of the gain medium [7], which for Ti:sapphire is: f_c = 700 kHz [5]. If df_0/dP changed significantly with the insertion of the knife edge, that could explain the narrowing of Δf_0 .

2. f_0 narrowing and dynamics

Figure 1a shows the laser configuration, with a 10 mm long Brewster-cut crystal of Cr:f, cooled to -5°C and pumped at 1075 nm by 8 W of power from a Yb:fiber laser (IPG Photonics). The pump laser is first passed through an AOM before entering the laser cavity, which is used to control and stabilize f_0. The laser output has a power of ~ 275 mW at a repetition rate of ~ 117 MHz, centered near 1275 nm, and the intracavity prism pair allows the spectral bandwidth to be continuously varied from ~ 35-55 nm.

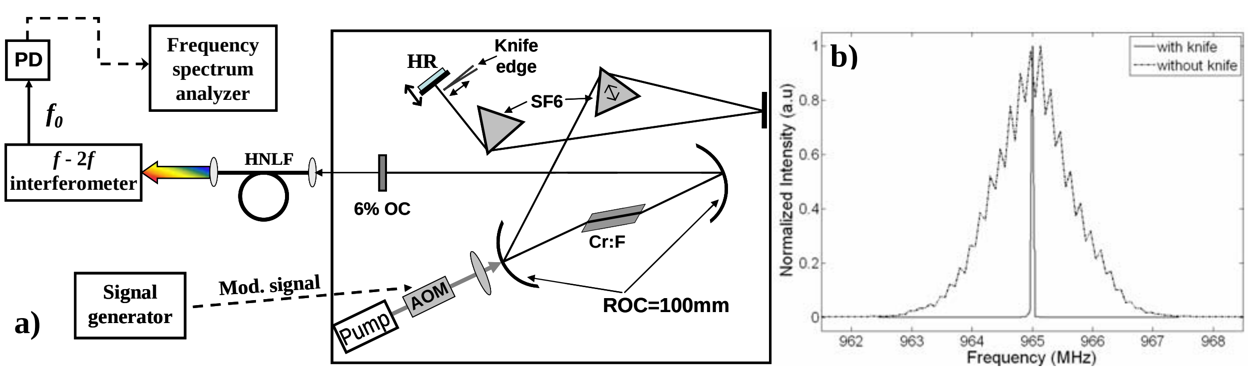

Fig.1: a) Cr:f laser cavity and f_0 detection configuration showing the knife edge, with HR = high reflecting endmirror, OC = output coupler, PD = photodetector. **b)** f_0 linewidth plots with the knife edge inserted (solid) and without the knife (dotted).

This output is then coupled into 10 m of highly-nonlinear fiber (HNLF) to broaden the optical spectrum to span an octave (in our case $\Delta\lambda \rightarrow 1.0$-$2.2$ µm), which is then directed into an f-to-$2f$ interferometer and f_0 is detected after the interferometer using a fast InGaAs photodiode (125 MHz). The knife edge is inserted from the longer wavelength region of the Fourier plane of the prism pair continuously tuning the power spectrum to shorter wavelength, by as much as 20 nm (see Fig.2.b inset). To measure Δf_0 it was first stabilized to some extent using a slow-speed (< 1 kHz) feedback loop to the prism insertion. An RF spectrum analyzer was used to make Δf_0 measurements with and without the knife edge using resolution bandwidths (RBW) of 1 MHz and 30 kHz respectively to measure the normal and narrow profiles. Figure 1b shows the data from these measurements with the knife edge insert (dotted) and without (solid). Without any power modulation Δf_0 for the normal and narrow profiles were ~ 1.5 MHz and < 30 kHz. The response of the slow-servo control of the prism limited our ability to make more precise measurements of the narrow profile. However it did give it an upper limit of Δf_0 = 30 kHz. Previous measurements have shown it to be closer to 10 kHz but this also requires fast servo control of the AOM.

One likely explanation for the reduction in f_0 linewidth with knife edge insertion is that the laser response to power fluctuations has changed considerably, either in amplitude or in frequency response. To test this idea, we again servo-controlled f_0 using the prism insertion and then measured df_0/dP by modulating the pump power with an AOM (whose frequency response was measured to be > 1.3 MHz) with an amplitude of about 4.5% or 350 mW peak-to-peak of the 8 W at frequencies between 250 kHz and 2 MHz. The resulting width of f_0 was measured, and the difference in width from the unmodulated state can then be attributed to the change in pump power. Figure 2a shows the result for both cases, with (dotted line) and without (solid line) the knife edge. The frequency cut-off is about 500 kHz in both cases, but the lack of an abrupt edge in the plot for the absent knife edge must be further explored. The ratio of amplitudes is about a factor 10 but the frequency response cut-off (f_c) is similar in both cases, with a roll-off at around 500 kHz. This increase can be related to df_0/dP by dividing the change in linewidth with and without modulation by the change in pump power, and is not large enough to fully explain the narrowing.

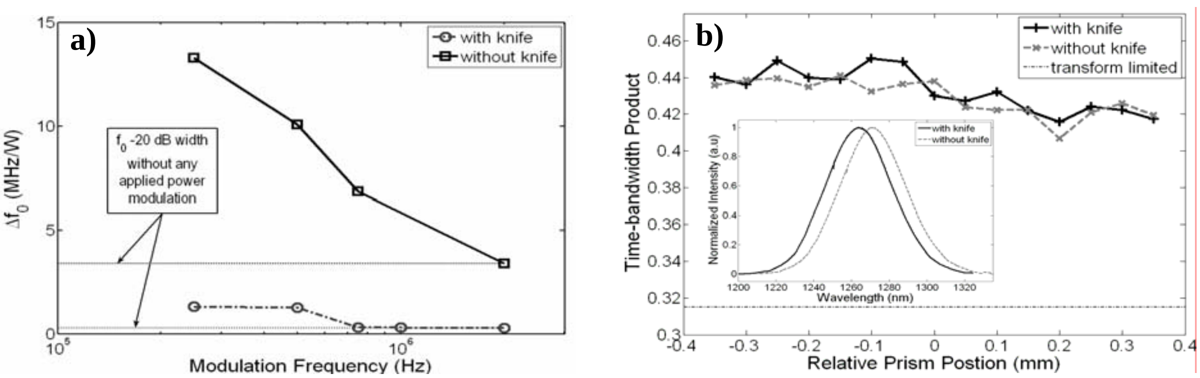

Fig.2: a) frequency response of f_0 width to fast power modulation with (dotted) and without (solid) the knife edge. **b)** Time-bandwidth product for our Cr:f laser with (thick dotted) and without (thick solid) the knife edge inserted compared to the transform limited case (narrow dotted), inset shows the difference in the power spectra with (solid) and without (dotted) the knife edge inserted.

3. Summary

To summarize we report on the dramatic reduction in linewidth of a Cr:f frequency comb simply by tuning the central wavelength of the laser output. The exact cause of the narrowing is not yet fully understood. Further investigations are currently underway to explain the cause of the narrowing and to stabilize the frequency comb with the narrow linewidth to enable us to make an absolute linewidth measurement. The results of these studies will be presented in detail and potential causes for the linewidth reduction will be discussed.

We would like to thank Jeff Nicholson and Man Yan for providing the HNLF, Scott Diddams and Nate Newbury for helpful discussions, and AFOSR and NSF for funding.

[1] D. J. Jones *et al*, 'Carrier envelop phase control of femtosecond modelocked lasers and direct optical frequency synthesis', Science, **288**, p. 635, **2000**

[2] K. Kim *et al*, 'Stabilized frequency comb with a self-referenced femtosecond Cr:forsterite laser', Opt. Lett., **30**, p. 932, **2005**

[3] R. Thapa *et al,* 'Phase-stabilized prism-based Cr:forsterite laser frequency comb for absolute frequency measurements', in Conference on Lasers and Electro-Optics (Optical Society of America, Baltimore, 2006), p. CMKK7

[4] K. W. Holman *et al*, 'Intensity-related dynamics of femtosecond frequency comb', Opt. Lett., **28**, p. 851, **2003**

[5] R. P. Scott *et al*, 'Amplitude and phase noise sensitivity of modelocked Ti:sapphire lasers in terms of a complex noise transfer function', Opt. Exp., **15**, p. 9090, **2007**

[6] B. R. Washburn *et al*, 'Response dynamics of the frequency comb output from a femtosecond fiber laser', Opt. Exp., **13**, p. 10622, **2005**

[7] J. J. McFerran *et al*, 'Suppression of pump-induced frequency noise in fiber-laser frequency combs leading to sub-radian f(ceo) phase excursions', Appl. Phys. B, **86**, p. 219, 2007