# Carrier-envelope offset frequency dynamics in a self-referenced prism-based Cr:forsterite frequency comb

Karl A. Tillman, Rajesh Thapa, Brian R. Washburn and Kristan L. Corwin
*J.R. MacDonald Laboratory, Kansas State University, Manhattan, KS 66506, U.S.A*

***Abstract:*** **Carrier-envelope offset frequency ($f_0$) dynamics of a prism-based modelocked Cr:forsterite laser are investigated in the context of a self-referenced frequency comb. Ultimately, this comb will be used in developing acetylene-filled fibers for portable frequency references.**

## INTRODUCTION

Considerable scientific interest is currently focused on the development of stabilized frequency combs due to the level of precision and stability they offer to applications such as optical frequency metrology [1], pulse synthesis [2] and high harmonic generation [3]. In these applications the primary concern is to control the carrier-envelope offset frequency ($f_0$) as this vital in understanding the nonlinear interactions when using few-cycle femtosecond pulses. Significant progress has been made in the development of self referenced frequency combs based on solid state lasers such as the Ti:sapphire which can offer a frequency stability of the order of sub-hertz with very narrow frequency linewidth. Interest from the telecommunications industry has also helped fuel the development of all fiber based comb systems [4] where there is a need for robust and compact devices capable of easy integration with current technology. Fiber lasers have improved dramatically over recent years [4] and now have narrow linewidths similar to Ti:sapp but lower typical repetition rates. Cr:forsterite lasers have the high repetition rates of other solid state lasers in the near IR, and are therefore of great interest. Kim *et al.* at the NIST have previously self-referenced a Cr:f laser based on chirped mirrors [5]. We have phase-stabilized a prism-based Cr:f frequency comb that offers the advantage of greater tuneability of the intracavity dispersion and have observed a narrower $f_0$ than measured by the group at NIST [6]. However, the ability to control the parameters of the frequency comb depends on many other parameters, which we are exploring here in order to improve the stability of our comb. We will then use the comb to characterize portable fiber-based frequency reference in the near IR[1] [7].

Any frequency comb has two degrees of freedom that must be controlled in order to generate a fully characterized and phase-stabilized output. These are the repetition frequency ($f_{rep}$) and the carrier-envelop offset frequency ($f_0$) and are determined by the group ($v_g/l$) and phase ($v_p/l$) delay (where $l$ is the cavity length) of the laser pulses which depend on the total intracavity dispersion of the lasers. Simple servo control of the laser cavity length enables very fine control of $f_{rep}$; however because the dependence of $f_0$ on $v_g$ and $v_p$ is more complex it is significantly harder to control than $f_{rep}$. A common approach utilizes the intensity-dependence of the laser gain mediums nonlinear refractive index to change the intracavity dispersion which is achieved by using an acousto-optic modulator (AOM) to modulate the pump power. In the case of prism-based solid state laser systems it has been shown that even for moderate pump power changes there is movement in the intracavity beam [8] changing the optical path around the cavity. This alters the dispersion contributions due to the intracavity prisms which then becomes a function of pump power in addition to the intensity dependence of the nonlinear refractive index of the Cr:f crystal. This means controlling $f_0$ will be inherently more complex for prism-based systems than for the prismless systems. With this in mind we present preliminary studies of the intensity related dynamics of $f_0$ for a prism based self-referenced modelocked Cr:f system.

## EXPERIMENT

The laser used in this study is based on a folded bow-tie cavity configuration that uses a 10mm long Brewster angled Cr:f crystal pumped at 1075nm by a 10W Yb:fiber laser (IPG Photonics) which is first passed through an AOM. The Cr:f crystal is cooled to -5°C and produces an output centered at 1250nm with an average power of ~230mW for pulse durations of ~35fs at a repetition rate of ~116MHz. The output is then coupled into ~10m of highly nonlinear fiber (HNLF) to generate a supercontinuum (SC) output that covers a wavelength range in excess of an optical octave (actual coverage is greater than 1.0-2.2μm). The output from the HNLF is then directed into an $f$-to-$2f$ interferometer commonly used in the self-referencing technique. The $2f$ arm of the interferometer contained a 10mm long crystal of periodically poled lithium niobate (with a grating period of 30.0μm) to generate a second harmonic (SHG) of the SC signal at 1030nm. The SHG signal when mixed with a narrowband filtered section of the SC signal from the $f$ arm of the interferometer (also at 1030nm) allows the $f_0$ signal to be detected directly. Both $f_{rep}$ and $f_0$ were detected simultaneously using a pair of 125MHz InGaAs photodetectors connected to two independent frequency counters. The modulation in pump power was controlled by an AOM driven by a variable-amplitude, square-wave TTL output from a signal generator. This was synchronized to a frequency modulating (FM) output from the same signal generator which was connected to a third frequency counter. $f_{rep}$, $f_0$ and FM were counted

[1] Funding for this project comes from AFOSR under grant no. FA9950-05-1-0304 and from the National Science Foundation under grant No. ECCS-0449295

1-4244-0925-X/07/$25.00 ©2007 IEEE 

simultaneously to detect any periodic changes in $f_{rep}$ and $f_0$ caused by the power modulation. The data were then analyzed to retrieve average $\Delta f_0$ values for given prism positions. Measurements were repeated using a range of different prism insertions while the pump power was continually modulated by ~250mWs around 8.9W at a rate of 5Hz. The change in power corresponds to an intensity change of ~$3.5\times10^9$W/m$^2$ using an estimated pump beam radius of 20µm

Figure 1 shows schematically the setup used in the experiment while Fig.2 shows preliminary results of the changes in $f_0$ for a given pump power change ($\Delta f_0/\Delta P$) across a range of different prism insertion. Figure 2 shows a clear dependency of $\Delta f_0/\Delta P$ on the total intracavity dispersion which will enable the $\Delta f_0$ response with pump power to be maximized allowing our servo control of $f_0$ to become more effective. This investigation along with other studies which are currently underway are necessary to understand the intensity dependant dynamics of $f_0$ in Cr:f. Using this and other data we hope to develop a theoretical model of the $f_0$ dynamics similar to that developed for the Ti:sapp laser [9].

Prior to carrying out these studies it was extremely difficult to frequency-lock the $f_0$ signal due to the presence of large fluctuations (10's of MHz). The magnitude of the pump power changes needed to compensate for these $f_0$ fluctuations were frequently sufficient to lose modelocked operation of the Cr:f laser. This limited our ability to lock $f_0$ and use heterodyne detection with a CW laser source in future work to develop portable frequency references. In summary these studies will allow us to develop a better understanding of the more influential aspects of $f_0$ jitter in prism-based self-referenced Cr:f frequency combs. In addition, these studies have enabled us to develop a method for locking $f_0$ over extended time periods using a combination of both intracavity prism modulation and pump power modulation.

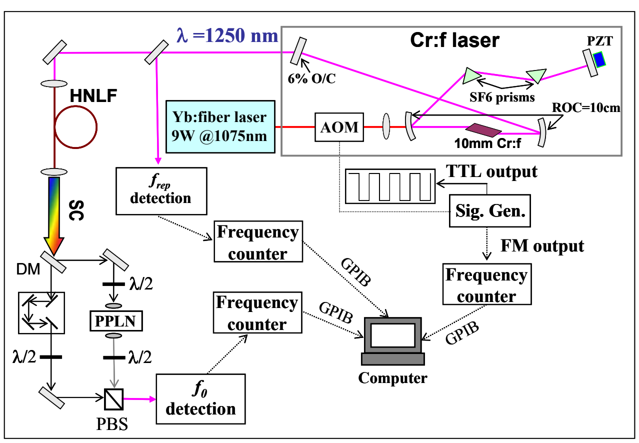


**Fig. 1:** Experimental configuration used to make $\Delta f_0/\Delta P$ measurements as a function of relative prism insertion. (DM=dichroic mirror, λ/2=half-wave plate, PBS= polarization beam splitter, O/C=output coupler, ROC=radius of curvature, Sig. Gen.=signal generator, all other abbreviations are given in the main text)

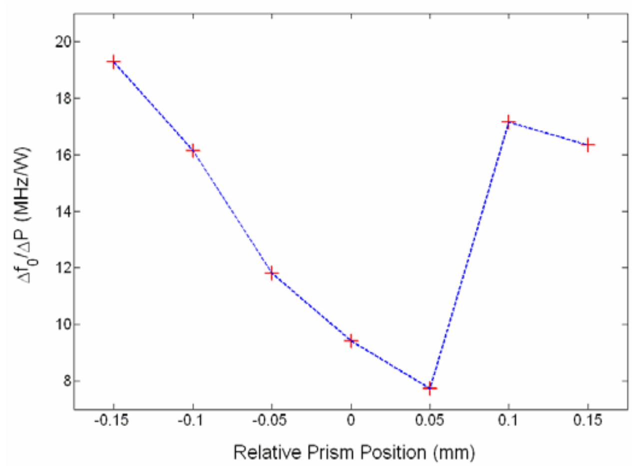


**Fig. 2:** Preliminary results showing a dependence of the $\Delta f_0/\Delta P$ signal with the relative prism insertion. A minimum in the $\Delta f_0$ response of is visible corresponding to a maximum required $\Delta P$ needed to maintain a fixed $\Delta f_0$.

## ACKNOWLEDGMENT

We would like to thank N. Newbury, S. Diddams and K. Read for many helpful discussions and J. Nicholson and M. Yan for supplying the HNLF fiber.

## REFERENCES

1. T. R. Schibli, *et al.*, "Frequency metrology with a turnkey all-fiber system". *Opt. Lett.*, 2004. **29**(21): pp. 2467-2469.
2. R. K. Shelton, *et al.*, "Phase-coherent optical pulse synthesis from separate femtosecond lasers". *Science*, 2001. **293**(5533): pp. 1286-1289.
3. A. de Bohan, P. Antoine, D. B. Milosevic,and B. Piraux,, "Phase-dependent harmonic emission with ultrashort laser pulses". *Phys. Rev. Lett.*, 1998. **81**(9): pp. 1837-1840.
4. B. R. Washburn, W. C. Swann, and N. R. Newbury, "Response dynamics of the frequency comb output from a femtosecond fiber laser". *Opt. Exp.*, 2005. **13**(26): pp. 10622-10633.
5. K. Kim, *et al.*, "Stabilized frequency comb with a self-referenced femtosecond Cr : forsterite laser". *Opt. Lett.*, 2005. **30**(8): pp. 932-934.
6. R. Thapa, *et al.*, "Phase-stabilized prism-based Cr:forsterite laser frequency comb for absolute frequency measurements". OSA *CLEO/QELS conference*, 6-11th May 2007. Baltimore, MA, *Conf. Proc.* CMKK7.
7. R. Thapa, *et al.*, "Saturated absorption spectroscopy of acetylene gas inside large-core photonic bandgap fiber". *Opt. Lett.*, 2006. **31**(16): pp. 2489-2491.
8. F. W. Helbing, *et al.*, "Carrier-envelope offset dynamics of mode-locked lasers". *Opt. Lett.*, 2002. **27**(3): pp. 194-196.
9. K. W. Holman, R. J. Jones., A. Marian, S. T. Cundiff, and J. Ye, "Intensity-related dynamics of femtosecond frequency combs". *Opt. Lett.*, 2003. **28**(10): pp. 851-853.