Transferring the Long-Term Stability of a GPS-Disciplined OCXO to Vescent's FFC-100 Optical Frequency Comb by Repetition Rate Locking.

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Summary: We demonstrate a straightforward method of locking Vescent's fiber frequency comb (FFC-100) repetition rate to any user-supplied RF oscillator. The general scheme for achieving this repetition-rate lock is shown in Figure 1. To demonstrate the power of this technique, here we lock the FFC-100 to an SRS FS740 GPS-disciplined oven-controlled crystal oscillator (OCXO) and show that the superb long-term frequency stability of the SRS FS740 is transferred faithfully to the frequency comb modes *(< 1E-12 fractional instability or <200 Hz optical frequency instability at 1550 nm on timescales >6 hours*) while retaining the short-term stability characteristic of the free-running comb tooth linewidths (*<2 kHz FWHM at 1550 nm*). This technique can be used for applications requiring precise frequency measurements. When properly calibrated to a known optical frequency standard (*i.e.,* through a heterodyne measurement between a single comb tooth and a spectroscopic standard), this relative instability can be translated to an absolute frequency accuracy to achieve ultra-high accuracy spectroscopy over the broad optical bandwidth of the frequency comb.

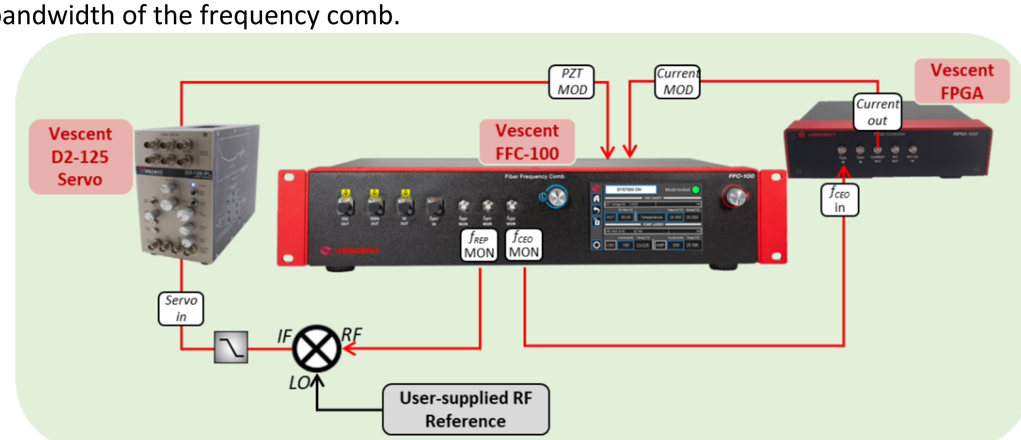

Figure 1. General scheme for repetition-rate locking the FFC-100 to a user-supplied RF reference.

Introduction: One of the many applications of an optical frequency comb is to act as a so-called "frequency ruler" with the capability to measure optical frequencies with extremely high precision over a broad bandwidth. While there are several specific techniques to enable this, the basic source of this capability comes from the simple relationship between every "tooth" of the comb spanning all the way from optical to RF frequencies:

$$(1) \quad f_n = f_{ceo} + n \cdot f_{rep}$$

In this simple equation, one immediately sees that every comb tooth, f_n, is related to just two RF comb parameter frequencies, f_{ceo} and f_{rep}. By locking these two comb parameters to stable references available in the RF, one can transfer the RF reference stability to the comb modes in the optical domain. In this application note, Vescent demonstrates a simple method to achieve this with the FFC-100.

Setup: The specific setup used by Vescent for this demonstration and the corresponding setup used to measure the resulting out-of-loop instability imparted to the FFC-100 is shown in Figure 2. First, the f_{ceo} comb parameter of a 100 MHz FFC-100 is locked using a Vescent SLICE-FPGA-II. The repetition rate, f_{rep}, is divided down in frequency by a factor of 10 (Valon Technology 3010a) and sent to the RF port of a low-noise phase detector (Mini-Circuits ZRPD-1+). The 10 MHz output of a GPS-disciplined OCXO (SRS FS740) is sent to the LO port of the phase detector and the IF port output is directed to the error input of a Vescent D2-125 servo controller. The FFC-100 repetition rate is phase locked to the GPS-disciplined OCXO with a simple proportional-integrator (PI) feedback to the FFC-100 PZT modulation input. The PZT modulation feedback offers high bandwidth but is limited in dynamic range. The dynamic range is sufficient to keep the FFC-100 locked in this way for tens of minutes depending on the specific environmental parameters experienced during operation. To enable long-term locking, a slow feedback loop is engaged to change the oscillator temperature set point to keep the PZT voltage centered at a nominal value. This slow feedback loop comes integrated into the FFC-100 and can be enabled via a text-based command or through the front-screen GUI.

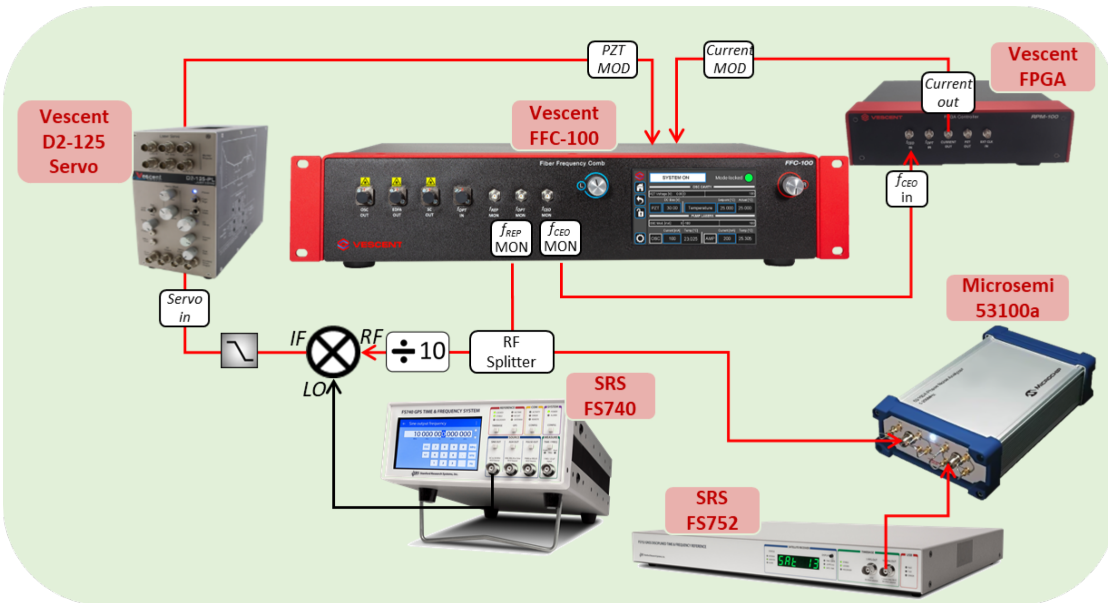

Figure 2. The specific scheme used by Vescent to lock the FFC-100 repetition rate to a GPS-disciplined OCXO (SRS FS740) and the measurement scheme used to accurately determine the FFC-100 out-of-loop instability achieved by this method.

The PID parameters of the D2-125 for f_{rep} locking were set to f_I = 20 Hz, f_{PI} = OFF, and f_D = OFF. The proportional gain was set to -10 dB. The f_I corner of the servo is kept to a low frequency (≤20 Hz) to retain the short-term stability of the free-running comb (*i.e.,* the "instantaneous linewidth" of the comb teeth) while imparting the long-term stability of the GPS-disciplined SRS FS740 onto the optical comb teeth. To achieve the f_{rep} lock, the frequency of either the OCXO synthesizer or the repetition rate of the comb can be manually tuned to closely overlap the frequencies of the RF and LO signals (within ~10 Hz) and allow the quadrature condition of their phases to fall within the dynamic range of the PZT feedback to the comb. Once this condition is met, the D2-125 servo can be enabled by pushing the switch into the "lock" position. The DC error monitor on the D2-125 can be viewed on an oscilloscope to ensure this error signal goes to zero and an AC RMS measurement of the noise on the DC error signal can be used to characterize the "tightness" of the lock.

Results: Ultimately what matters to the present application is how well the stability of the GPS-disciplined OCXO was transferred to the frequency comb repetition rate. To measure this, two Allan Deviation Measurements are compared using the Microsemi 53100a timepod: (1) the SRS FS740 10 MHz output signal is measured directly against the SRS FS752 10 MHz output (note: the choice of different GPS units was based on available equipment at hand). The corresponding Allan deviation gives the out-of-loop fractional instability between these two different GPS-disciplined OCXO's, plotted as a blue line inv Figure 3(A). In the next measurement, (2), the frequency comb f_{rep} is locked to the SRS FS740 as described above and the fractional instability of f_{rep} split off from the locked frequency comb is measured against the SRS FS752 10 MHz output. The corresponding Allan deviation gives the out-of-loop fractional instability of the locked frequency comb relative to the SRS FS752 GPS-disciplined OCXO and is plotted as an orange line in Figure 3(A) (fractional instability shown on the right axis). Comparing these two measurements clearly demonstrates that the frequency stability of the SRS FS740 is transferred to the frequency comb rep rate with high fidelity, especially at timescales >1s. Due to the simple relationship between the optical comb teeth frequencies, f_n, and f_{rep} shown in Equation (1), the absolute frequency instability of the optical comb teeth is simply:

$$(2)\ \delta f_n = \delta f_{ceo} + n \cdot \delta f_{rep}.$$

For comb teeth at 1550 nm, $n \approx 1.92 \times 10^6$, which essentially makes the δf_{ceo} term negligible relative to the $n \cdot \delta f_{rep}$ term. The corresponding optical instabilities of the frequency comb at 1550 nm are shown on the left axis for the orange data line in Figure 3(A).

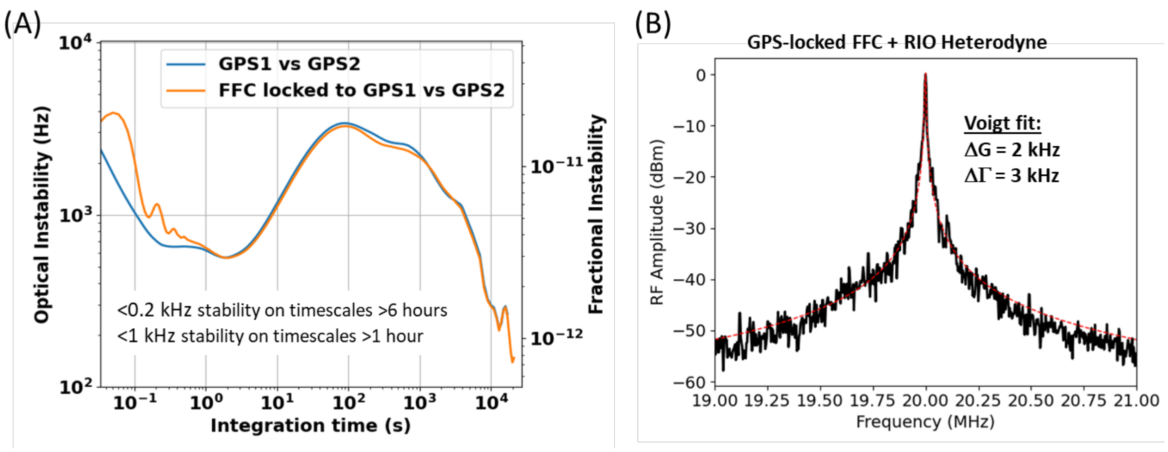

Figure 3(A) Allan Deviation and (B) linewidth measurements. The optical instability in (A) was measured near 1550 nm.

One potential disadvantage to locking an optical frequency comb to an RF source, is that the optical frequency multiplication shown in Equation 2 can lead to a degradation of the short-term instability (*i.e.,* the linewidth and ultimately the phase noise) of the optical comb teeth. In general, the fractional frequency noise of the free-running frequency comb at high-offset frequencies (usually associated with the "instantaneous linewidth") is superior to that of any RF reference, while being inferior at low-offset frequencies (associated with frequency instability or drift). By purposefully setting the f_I corner to a low frequency (20 Hz in this case), the superior high-offset fractional frequency instability of the free-running frequency comb can be preserved while still gaining the advantage of the long-term stability of the RF reference. This is clearly shown from the linewidth measurement in Figure 3(B), where the linewidth of a heterodyne signal between a 2 kHz linewidth RIO laser and an optical tooth of the locked frequency comb is measured to be <5 kHz. A Voigt fit is used to capture the small amount of Gaussian broadening occurring due to the f_{rep} locking scheme.

Conclusion: A simple scheme is presented showing that Vescent's fiber frequency comb can be tightly locked to a GPS-disciplined OCXO with long-term stability transferred to the optical comb teeth without degrading the short-term optical linewidth of the free-running comb.