Towards an Integrated-Photonics Optical-Frequency Synthesizer With <1 Hz Residual Frequency Noise

Daryl T. Spencer[1*], Aaron Bluestone[2], John E. Bowers[2], Travis C. Briles[1], Scott A. Diddams[1], Tara Drake[1], Robert Ilic[1], Tobias J. Kippenberg[3], Tin Komljenovic[2], Seung Hoon Lee[6], Qing Li[4], Nathan Newbury[1], Erik Norberg[5], Dong Yoon Oh[6], Scott Papp[1], Martin H. P. Pfeiffer[3], Laura Sinclair[1,] Kartik Srinivasan[4], Jordan Stone[1], Myoung-Gyun Suh[6], Luke Theogarajan[2], Kerry Vahala[6], Nicolas Volet[2], Daron Westly[1],Ki Youl Yang[6]

[1]*National Institute of Standards and Technology, Boulder, CO 80305 USA*
[2]*University of California Santa Barbara, Santa Barbara, CA 93106 USA*
[3]*Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland*
[4]*National Institute of Standards and Technology, Gaithersburg, MD 20899 USA*
[5]*Aurrion Inc., Goleta, CA 93117 USA*
[6]*California Institute of Technology, Pasadena, CA 91125 USA*
**daryl.spencer@nist.gov*

Abstract: We introduce an architecture for optical-frequency synthesis using photonic-chip frequency combs and a heterogeneously integrated CW laser. The Kerr dual-comb that we describe offers a microwave-optical link to discipline the laser to an RF clock.

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1. Introduction to optical-frequency synthesis with integrated photonics

The coherent phase link between laser light and microwave radiation enabled by optical-frequency combs has opened various new research directions, including optical timekeeping, molecular spectroscopy, laser ranging, optical communications, and quantum science [1,2]. Heterogeneous photonics will enhance the reach of these, and create still new directions, by making available low-cost, deployable systems of lasers, modulators, photodetectors, and other components that can harness novel nonlinear photonics processes in chip-integrated materials. Here we introduce a specific heterogeneous photonics system designed to synthesize the frequency of laser light relative to an RF clock. Maturing III/V-Si heterogeneous lasers provide a widely tunable yet narrow linewidth source, and recently developed Kerr-microresonator frequency combs close the loop between the tunable laser's frequency and an RF reference clock. Our paper introduces these core elements of the optical synthesizer with emphasis on the first measurements of low-noise performance in an octave-span, chip-based Kerr comb and demonstration of <1 Hz residual noise performance in stabilizing an integrated tunable laser to a Kerr comb.

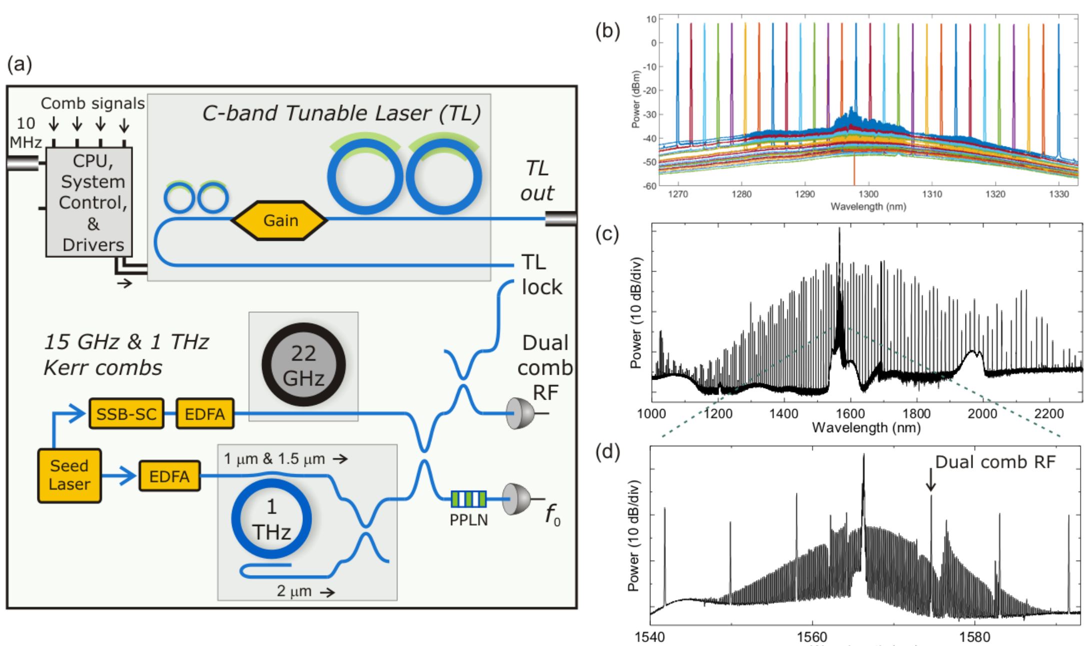

Figure 1: Heterogeneous photonics system for optical frequency synthesis. (a) System components include a Vernier ring tunable laser with III/V-Si heterogeneous integration, and a dual microresonator Kerr comb based on a 22 GHz silica device and a 1 THz silicon-nitride device operating in the low noise soliton regime. (b) Tunable laser tuning spectra for this demonstration. (c) Octave-bandwidth dual Kerr comb with dual dispersive waves for f-2f self-referencing and dense mode spacing near the 1550 nm pump. (d) Zoom of (c) showing the dense 22 GHz silica comb.

Figure 1a presents a schematic of the integrated optical-frequency-synthesizer system and the key optical spectra that characterize it. The overall system output relies on an integrated Vernier laser capable of >50 nm tuning across the same wavelength region as the dual-comb's pump laser. A dual-microresonator Kerr frequency comb provides the microwave-optical link to discipline the tunable laser and provide an accurate, low noise output. In this system, we pump the dual-combs near 1550 nm, but demonstrate low noise locking of an O-band tunable laser to the THz comb that is similar in production to future C-band lasers. The need to incorporate two different combs arises from fundamental power consumption and bandwidth tradeoffs in Kerr frequency combs. To obtain an octave bandwidth spectrum it is favorable to leverage a silicon-nitride microring with very large 1 THz mode spacing [3]. Conversely, to obtain a 10's of GHz mode spacing comb spanning the C-band, we leverage the uniquely high Q and chip-compatible silica platform [4]. Figure 1c-d show the output optical spectra of the tunable laser and the dual Kerr comb. Importantly, the 1 THz comb spans more than an octave to enable f-2f self-referencing, and the silica comb serves the dual purpose of detecting the 1 THz spacing and providing a dense grid of reference modes. Both frequency combs operate in the low noise soliton regime.

2. Photonic elements with low-noise performance

The chip-scale optical frequency synthesis approach we describe involves low pump power monolithic microresonators of two different repetition frequencies. A waveguide coupled Si_3N_4 THz microcomb with a radius of 23 μm and height of 600 nm is used to generate octave bandwidth efficiently to enable f-2f interferometry and carrier-envelope offset frequency detection [3]. The on-chip pump power used is approximately 100 mW. The pump laser is split and passed through a single-sideband suppressed-carrier (SSB-SC) modulator for rapid, independent excitation of a silica based single soliton, Figure 1d [4]. The repetition frequency of this comb is 22 GHz, enabling detection with microwave photodetectors. Combined with the heterodyne beat between the two combs 1 THz away from the common pump, the exact spacing of the THz microcomb is measured (Figure 2a). We detect the carrier-envelope offset frequency with the help of an external cavity diode laser (ECDL) tuned to nearly match the THz comb mode near 1984 nm. After passing the ECDL light through a Thulium amplifier (≈15 dB gain) and a waveguide coupled PPLN device with 5%/W total efficiency, an optical heterodyne with the THz comb produces two RF tones on photodetectors; which are shown in Figure 2b-c. Using the two RF beats, δ_{992} and δ_{1984}, and knowing the pump laser is at the THz comb mode number of 191, any other frequency in the comb can be determined by $f_n = N * f_{rep} + 2 * \delta_{1984} - \delta_{992}$ for synthesizing arbitrary frequencies with the tunable laser. Both of these heterodyne signals indicate that the THz comb modes at these wavelengths have <1 MHz linewidth, and that the carrier offset frequency is approximately 7 GHz. Further, these signals offer sufficient SNR for electronic processing to remove their contribution from the ECDL and for subsequent phase locking of the dual Kerr comb pump laser. Our presentation will report on progress towards full frequency stabilization of the dual Kerr frequency comb referenced to a microwave clock.

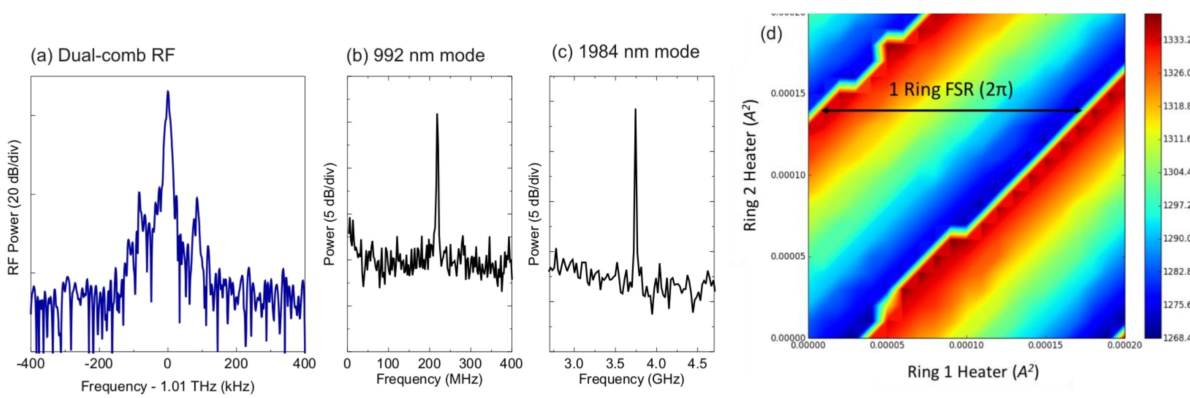

Figure 2: RF outputs of the dual Kerr comb indicating low-noise operation. (a) Repetition rate beat between the pump THz and silica comb, (b) 992 nm heterodyne beat with the second harmonic generation of the ECDL, and (c) 1984 nm heterodyne with the ECDL. (d) Tuning map of the O-band tunable laser for this demonstration, showing mode hope free tuning using the two ring resonators.

The widely tunable laser, which will be locked to a dual-comb mode, is based upon the heterogeneous Si/III-V platform developed by Aurrion Inc. The laser includes III/V gain material, monolithically integrated Si loop mirrors, 2 intracavity add-drop filters for linewidth narrowing, and thermal phase tuners to adjust the round trip phase and each filter's resonance wavelength [5]. With this Vernier effect and thermal tuning capability over 54 nm, optical synthesis over the entire laser tuning range is possible while being tightly referenced back to the main THz frequency comb. The full tuning map of the laser shows full mode hope free tuning over the resonator's free spectral range, Figure 2d.

3. Integrated tunable laser locking results

We explore phase locking of the integrated tunable laser to both a reference CW laser or to a single THz comb mode. Our work begins to incorporate advanced optical metrology techniques proven by fiber frequency combs [6]. Frequency tuning across the entire O-band of the tunable laser is achieved through heaters on the two ring resonators and intracavity phase section. The heater thermal time constants allow modulation up to 10 kHz, while the drive current on the SOA offers GHz of modulation bandwidth but with lower gain and wavelength range. For these reasons, the optimal design will implement a dual-loop with fine, high-speed feedback on the SOA current and coarse, low-bandwidth feedback on the ring resonators' heaters. For the phase-locking demonstrations presented here, FPGA-based electronics were used with a 100 MS/s sampling rate with feedback solely to the SOA current. For larger offset frequency phase locks to the comb, more advanced signal processing will be implemented including use of an electronic voltage controlled oscillator to down convert the signal to more manageable frequencies.

We observe greater than 60 dB reduction in the in-loop frequency noise at 100 Hz offset when feedback to the SOA current is used to phase-lock the tunable laser to the reference CW laser. A maximum feedback bandwidth of ≈100 kHz is found. The stability of the free-running THz comb is such that the tunable laser can also be phase-locked to a single tooth of the THz comb. Using the same FPGA-based electronics, the frequency of the 25-MHz beat between the THz comb tooth and the tunable laser was counted for 15 minutes. By monitoring the in-loop frequency noise, Figure 3a, we observe the loop servo reducing noise up to a 10 kHz bandwidth and down to 100 Hz^2/Hz. Using a built in zero dead time counter with 1 second gate time, we observe less than 10 mHz drift over 15 minutes on the beat note deviation from the reference frequency, as shown in Figure 3b.

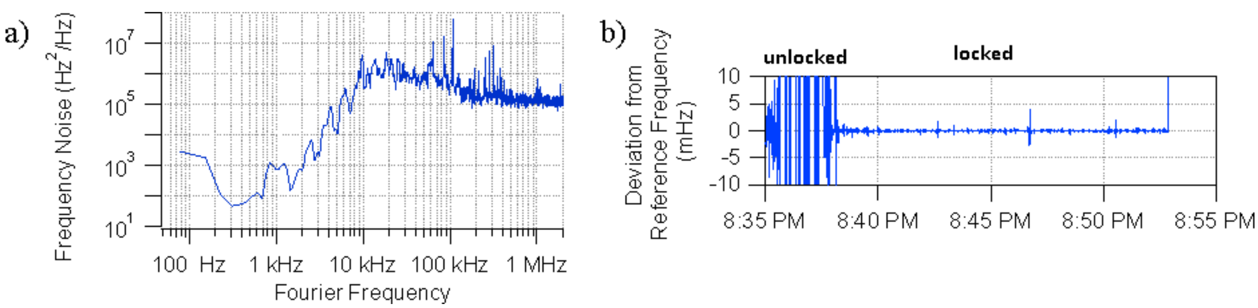

Figure 3: Results of the O-band tunable laser locked to the THz comb. (a) In-loop PSD of locked frequency noise, and (b) 1 second gate in-loop counter measurement for locking greater than 15 minutes.

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