Fiber-Optic Demonstration of Optical Frequency Division for Erbium Silicon Photonics Integrated Oscillator

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Abstract: Using fiber-optic components, we demonstrate an optical frequency division scheme for a proposed erbium silicon photonics integrated oscillator. An 80-dB division ratio from 192 THz to 1 GHz is achieved without an f-2f interferometer and carrier-envelope-phase locking.

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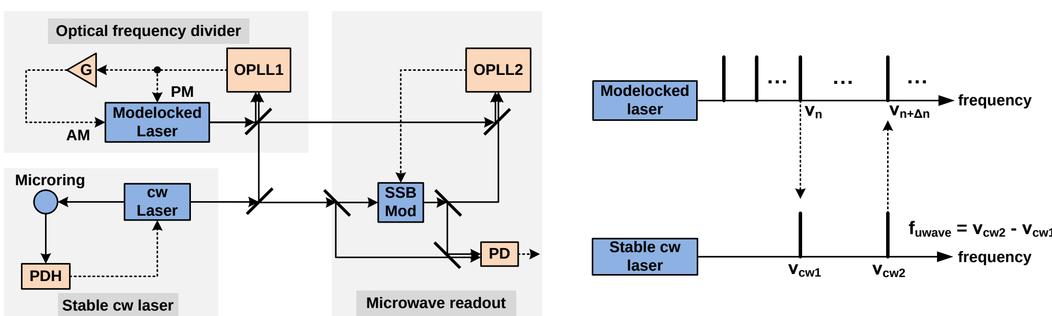
Photonic microwave oscillators based on optical frequency division (OFD) and an ultrastable continuous-wave (cw) laser stabilized to an optical reference cavity represents the state-of-the-art solution to generate X-band microwaves of ultralow phase noise [1]. One obstacle to widespread use of this technology is its large footprint and sensitivity to environmental perturbations. The advance in silicon photonics and wafer-scale three-dimensional integration technology illuminates pathways towards a fully-integrated photonic microwave oscillator architecture on a common silicon substrate platform [2, 3]. However, a number of challenges arise from current limitations of on-chip devices. The most important one is the difficulty of implementing carrier-envelop-offset frequency (f_{ceo}) stabilization with a standard f-2f interferometer. OFD effectiveness depends on frequency comb dynamics, and it does not necessarily reduce phase noise of the comb spacing without f_{ceo} stabilization. Another issue is the low power level of integrated modelocked lasers that increases photodetection noise when microwave are read out by detecting the laser pulse train.



(a) (b)

Fig. 1. Schematic of the ESPIO. (a) System architecture. Solid lines are optical paths, and dashed lines are signal paths. (b) Frequency domain illustration. OPLL, optical phase locked loop. SSB Mod, single-sideband modulator; PDH, Pound-Drever-Hall loop; PD, photodetector. AM, amplitude modulation. PM, phase modulation.

The proposed architecture of an Erbium Silicon Photonic Integrated OscillatoR (ESPIOR) circumvents the on-chip f-2f interferometry, and utilizes power surplus of the cw laser to boost comb line power. As shown in Fig. 1, the ESPIOR includes a cw silicon-nitride (SiN) waveguide laser [4] stabilized to a high-Q SiN microring, a modelocked laser as the optical frequency divider, and a microwave readout stage. The cw and modelocked lasers can be pumped at either 980nm or 1480nm, and erbium-ytterbium co-doping can be employed to enhance the absorption at 980nm and improve signal gain. The n^{th} comb line of the modelocked laser is phase locked to the cw laser frequency ν_{cw1} through an intracavity phase modulator that varies cavity optical length. In addition, an intracavity amplitude (or loss) modulator is modulated proportionally to the length change. The gain block G is configured in such a way that the summation of Δf_{ceo} due to the PM and AM are kept to be zero, which is equivalent to f_{ceo} stabilization. Experiments have shown that both amplitude and phase of the transfer functions are reasonably flat within their respective bandwidths [5], and therefore G could simply be a DC-coupled electronic amplifier with enough gain and bandwidth. To extract microwaves, a second single-frequency ν_{cw2} is generated by a single-sideband (SSB) phase modulator that shifts ν_{cw1} by a multiple of the repetition-rate f_r. It is then phase locked to the $(n+\Delta n)^{th}$ comb line. When beating the two single frequencies on a photodetector, microwaves can be extracted. This is equivalent to repetition-rate multiplication, but alleviates photodetector saturation in the case of photodetecting the pulse train.

While silicon photonics components of the ESPIOR are being studied and tested, a bench-top demonstration of the ESPIOR is constructed using off-the-shelf fiber-optic components and erbium fiber lasers. The stable cw laser employed in the demonstration is an Ethernal SlowLight laser from Orbits Lightwave. Currently without an external ultrastable cavity, the linewidth of 1ms observation time is ~400Hz. The modelocked laser is a 250MHz M-Fiber series erbium fiber frequency comb from Menlo Systems. Frequency comb dynamics of the same type have been previously reported [5]. Modulation bandwidths of the PZT and pump power are ~10kHz and ~50kHz, respectively. The phase locked loops include frequency dividers, digital phase detectors and proportional-integral loop filters. The SSB modulator is a lithium niobate device driven by a low-noise voltage-controlled oscillator.

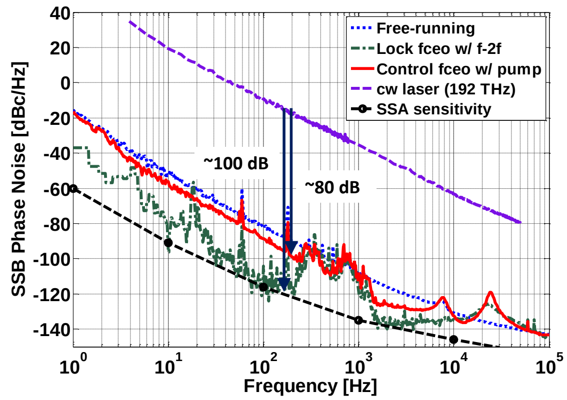


Fig. 2. Phase noise when f_{ceo} is controlled by synchronous pump modulation and when it is stabilized by an f-2f interferometer.

Fig. 2 shows the phase noise at 1-GHz carrier frequency after frequency division. The comb line is phase locked to the narrow-linewidth cw laser via the intracavity PZT. Microwaves are read out by directly photodetecting the optical pulse train, and phase noise is measured with a signal source analyzer (SSA). To compare OFD effectiveness, f_{ceo} is either detected and stabilized with the conventional method, or controlled by the proportional gain G without f-2f detection. In both cases, pump power is modulated to alter f_{ceo}. The lowest phase noise (red), is achieved at G = ~15dB. It corresponds to a 10-dB noise reduction compared with the free-running phase noise (dotted blue). Further increasing the gain G would break the PZT loop locking. The OFD ratio, compared with the case when f_{ceo} is locked with an f-2f interferometer (dash-dotted green), is currently limited by the PZT and pump modulation bandwidths, and the cross-talk of the two modulation mechanisms. Additionally, we have implemented the proposed microwave readout method. The phase noise of the regenerated microwaves follows that obtained by direct photodetection of the laser pulse train, and is currently limited by the PZT loop bandwidth around 10kHz. To improve the OFD ratio, intracavity modulators could be used instead. An intracavity electro-optic modulator can extend the cavity optical path length modulation speed to > 100MHz. An intracavity acousto-optic modulator can be used as a fast loss modulator of > 5MHz bandwidth.

In conclusion, we have demonstrated OFD of a narrow-linewidth cw fiber laser without f_{ceo} detection using an f-2f interferometer. Cross-talk of cavity length modulation and synchronous pump power modulation cancels out f_{ceo} fluctuation, so that comb-line frequency is primarily altered by the comb-spacing. In this way, an OFD ratio of > 80 dB from 192 THz to 1 GHz is achieved. To improve the OFD ratio, we are currently implementing high-bandwidth intracavity modulation components into the modelocked laser. Meanwhile, an ultrastable rigid Fabry-Pérot cavity will be put in place to reduce phase noise of the cw fiber laser. A second ESPIOR demonstration system will also be built for low-noise microwaves characterization. The demonstration is an important step towards on-chip OFD.

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