Nonlinear silicon photonics for optical frequency synthesis

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ABSTRACT

Optical frequency synthesizer, an optical counterpart of electronics frequency synthesizer is shown at chip scale using silicon photonics. We utilize the nonlinear properties of silicon, namely 3rd and electric field induced 2nd order effects for *f-2f* self-referencing. The frequency instability obtained in the telecom band is $1x10^{-12}$ at 1s level, comparable to a bench-top commercial optical frequency synthesizer system. An all on-chip silicon frequency synthesizer will have applications in the next generation optical communication, spectroscopic, detection and ranging systems making them widely available using the CMOS facility.

Keywords: Frequency synthesiser, ultrafast nonlinear optics, integrated optics, supercontinuum generation.

1. INTRODUCTION

An optical frequency synthesizer, which is phase coherently linked to the microwave frequency has various applications ranging from coherent communication, frequency metrology and optical atomic clocks [1-4].

Optical comb systems, produced through nonlinear optical processes, enable precision optical frequency synthesis in which a continuous wave (CW) laser source can be phase-locked and tuned over the wide bandwidth of a phase-locked frequency comb, to synthesize precise optical frequencies on demand. Recently a heterogeneously integrated optical frequency synthesizer was demonstrated [5]. To produce on a mass –scale, such systems need to leverage the well-established CMOS foundries. To this end, we demonstrate a silicon on insulator based optical frequency synthesizer.

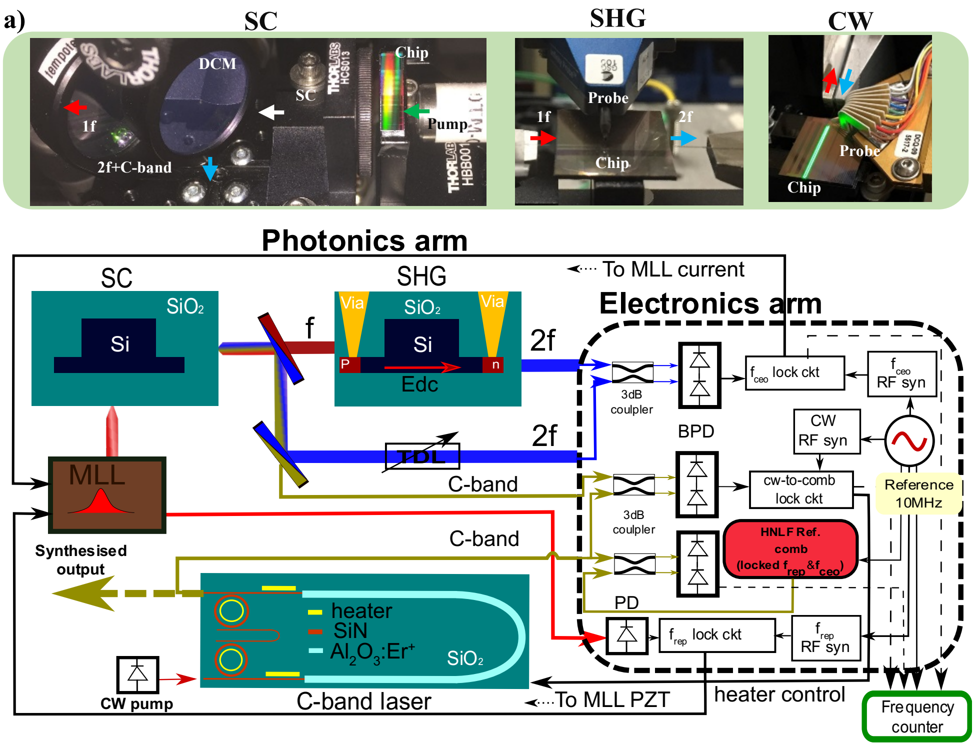

Fig.1 a) The images of the experimental setup for the supercontinuum (SC), second harmonic generation (SHG) and the tunable CW laser. b) The SPOFS circuit with its photonics and electronics arms. DCM: Dichroic mirror, TDL: Tunable delay line, BPD: Balanced photo diode, PD: Photodiode. The colored and black arrows are for optical and electronic signals. Solid and dashed lines from the RF reference (10MHz), are for locking the respective circuits and reading the values in the frequency counter, respectively. Synthesized output signal (dashed arrow from the CW laser).

The knowledge of the absolute frequency of an optical source, which is given as $f_{cw} = Nf_{rep} \pm f_{ceo} \pm f_{beat}$ in a comb system, lies at the heart of a frequency synthesizer. Here, N, f_{rep} and f_{ceo}, are the mode number, repetition frequency and the offset frequency of the mode locked laser, and the f_{beat} is the beat frequency between the CW laser and the mode locked laser (MLL) comb. We detect the f_{rep} by simply impinging a small amount of MLL signal onto a photodiode, and the f_{ceo} is detected by the silicon-based *f-2f* self-referencing scheme. Here, an MLL operating at 1.9 µm (thulium gain) producing <20 pJ pulses and <100 fs duration was used to pump a silicon waveguide to generate an octave spanning supercontinuum [6] as shown in Fig. 2(a). The *f* part around 2.3 µm was frequency doubled in an electric field induced quasi phase matched silicon waveguide [7]. The experimental and simulated SHG signal is shown in Fig. 2c. The second harmonic signal bandwidth and strength depends on the applied DC field and the group velocity mismatch between the *f* and the *2f* signal, the higher it is the lower the conversion bandwidth. The group velocity curve for the SHG waveguide is shown in Fig. 2d. The frequency doubled signal is mixed with the *2f* signal of the SC to obtain the f_{ceo} of the MLL, whose beat note is shown in Fig. 2(b). All of these frequencies are locked to a common RF reference (10 MHz), using their respective locking circuits, as shown in Fig. 1. To measure N of a low f_{rep} mode-locked laser, due to the lack of a wavemeter, a technique in which f_{rep} is slightly varied multiple times using PZT (in proportion to the CW laser linewidth) is employed [8]. We measured N with an error better than ±0.5 [9], which will improve further with an all integrated system down to <±0.02.

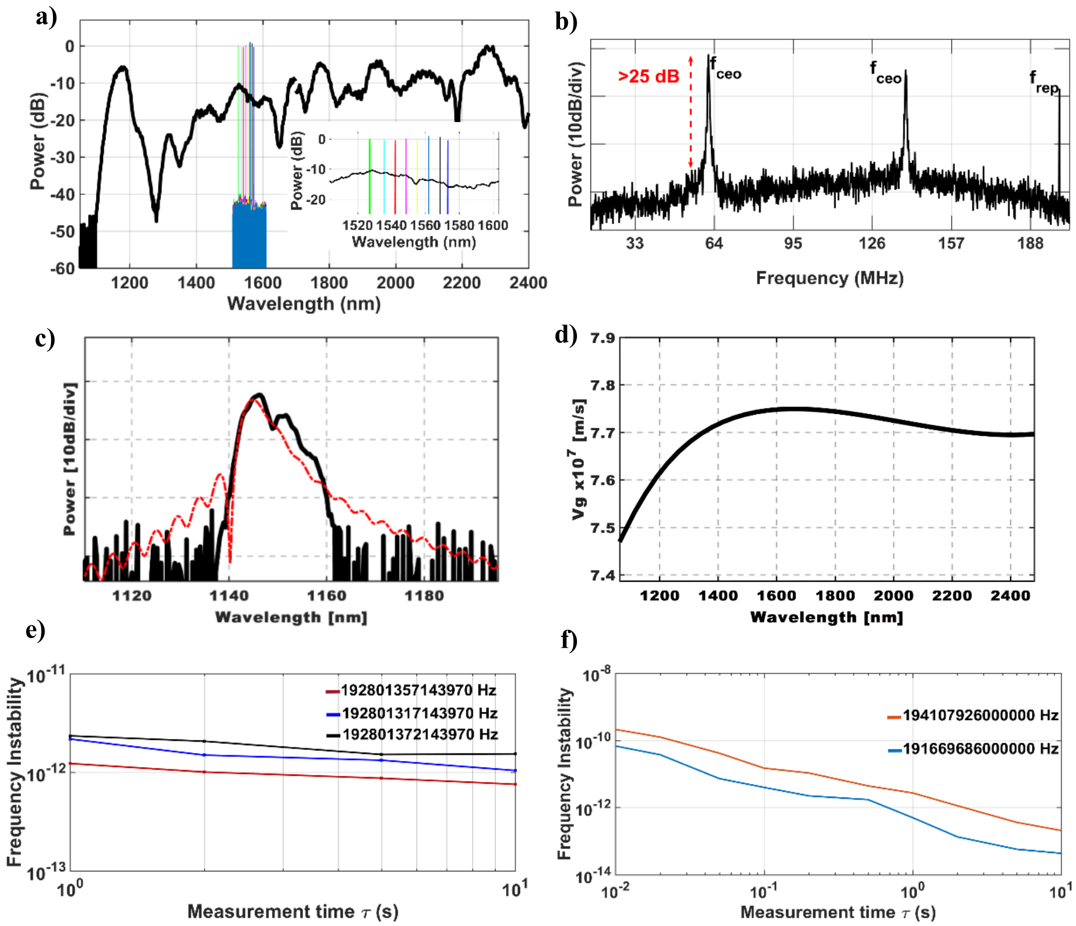

Fig.2 a) The SC spectrum with the CW laser tuning spectrum b) Measured f_{ceo} signal. c) The experimental and simulated SHG signal. d) the group velocity curve for the EFISH waveguide. e) Out-of-loop frequency instability measurement at three different frequencies f) Out-of-loop frequency instability measurement using commercial HNLF comb, showing 20 nm range tuning capability of the CW laser [6].

The absolute frequency instability of the silicon frequency synthesizer was determined using an external, out-of-loop, reference comb based on a highly nonlinear fiber (HNLF) which was also locked to the same RF reference (as shown in Fig.1). The beat between the silicon-comb stabilized CW laser and the reference comb for three different frequencies are shown in Fig 2(e), which were tuned to using the integrated heaters of the CW laser [10]. We achieved a frequency instability of $1\text{x}10^{-12}$ @ 1s level comparable to a commercial comb system. The tuning range was kept limited due to the combination of unavoidable high coupling losses of the SC signal at the telecom window (due to the use of free space optics), and the thermal fluctuations of the CW laser (due to the end-fire fiber coupling), which compromised the locking strength. To confirm that, we used a significantly stronger SC signal using a commercial HNLF comb and demonstrated a tight lock, enabling a 20 nm tuning range in the C-band (Fig. 2 (f)). Thus, with an all integrated system the coupling loss and the thermal fluctuations will be entirely suppressed. The frequency instability slope can be improved to be $1/\tau$ by taking data with multiple gate times set in the frequency counter, as in Fig 2(d).

2. CONCLUSIONS

In conclusion, we have demonstrated a silicon photonics optical frequency synthesizer with frequency instability comparable to a commercial system. In future we will integrate to the frequency synthesiser an efficient rare earth doped (thulium) silicon based mode locked laser.

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