Silicon Photonics Optical Frequency Synthesizer

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The knowledge of the exact frequency of an optical source has always been one of the ultimate goals in optics. Since the discovery of the laser, complex systems have been developed to address this challenge. That effort reached a significant milestone with the advent of the femtosecond laser frequency comb that reduced the system size from an entire lab down to the bench-top. That spurred interest in the development of integrated optical frequency synthesizers that can generate precisely different optical frequencies on demand and can be deployed widely. In this work, such an optical frequency synthesizer using supercontinuum waveguide and second harmonic generator on silicon photonics platform is demonstrated. Integrated silicon photonics based tunable continuous wave laser is phase-locked to a microwave reference, to synthesize absolute optical frequencies in the telecom band. A relative frequency instability of $1 \times 10^{-12}$ at 1 second level is achieved by utilizing an integrated self-referencing scheme that exploits the strong 3rd order and electric-field-induced 2nd order nonlinearities of silicon waveguides. With this work, an all on-chip silicon photonics based frequency synthesizer seems promising for mass production of next generation broad-band coherent optical communication systems, spectroscopic, detection, and ranging systems and future integrated quantum systems with Hz-level precision.

1. Introduction

An optical frequency synthesizer based on optical frequency combs[1,2] is an optical counterpart of an electronic frequency synthesizer based on phase-locked loops that has played a pivotal role in the evolution of modern electronics and telecommunication systems since the mid-20th century. From military applications in radar and navigation to consumer electronics the use of electronic frequency synthesizers is ubiquitous due to their implementation as precise frequency generators, local oscillators, modulators, and demodulators. As optical systems are taking over from electronics to serve the ever-increasing demand in bandwidth, an integrated optical frequency synthesizer seems to be an obvious device of future communication systems. Not only will it find applications in low energy/bit broadband coherent communication and quantum systems[3-6] but also in quantum level spectroscopy and sensing, detection and ranging, high precision global positioning systems, synchronizations of high energy accelerator sources, and portable optical atomic clock.[7-11]

Optical frequency synthesizer has been sought-after since the invention of the laser. It is a device that generates optical frequencies on demand that are phase coherently linked to a microwave reference, thus allowing precise knowledge and synthesis of the optical frequencies with respect to the unit of time “second,” which is based on a microwave reference, for example a cesium clock.[1,2] The most demanding part of a synthesizer is the link between the optical and the microwave domain. Before the 90s highly complex and challenging frequency multiplication chains were constructed, starting in the 60s by Javan and co-workers[12] In this approach, the low frequencies are multiplied by nonlinear devices (diodes for a few THz and nonlinear crystals for 100s of THz) to create a link between the microwave reference to one specific optical line, which would still be many THz away from the target optical frequency. Such bulky and formidable frequency chains could only be afforded by a few national labs.[13,14] To make the synthesizer more accessible and reduce the gap between the countable optical frequency and the target frequency, around the 90s new ideas emerged based on frequency division using second order optical nonlinearity. For example, using multiple optical parametric down converters from an unknown frequency down to a known reference,[15] and frequency bisection technique
where the difference between the two unknown frequencies are bisected exactly in half by the second harmonic of a third laser to reach microwave domain with successive bisections. All of these techniques, however, needed several nonlinear stages and were prone to systematic errors, and even then did not fully reach the target frequency. Optical combs generated through mode locked lasers or electro optic modulators were considered to create the link, however, it was not until late 90s that the breakthrough came when stable Ti:sapphire modelocked lasers were introduced for frequency metrology by Hänisch’s group (21,22) that significantly reduced the size of the system and made it more accessible. Together with the newly developed photonics crystal fibers (23) the combs lines of a modelocked laser could now be spread for the first time over a large bandwidth (550 THz), generating white light continuum through Kerr effect (24) connecting microwave to optical frequencies. With this approach, the repetition rate and the carrier envelop offset frequency (which arise due to the difference in the group and phase velocities in a medium) that define all the optical comb lines of a modelocked laser could now be referenced to a microwave frequency with the help of self-referencing scheme (22,25) thus completing the optical to electronic link. With such a system, frequency of an unknown laser lying anywhere in an octave spanning comb could be precisely determined with respect to a microwave reference.

Optical frequency synthesizers have come a long way since the days of frequency multiplication chains. However, their benchtop form still prohibits their applicability to various technologies that require micro to nano scale devices. Recently, there has been a notable progress in frequency comb technology at chip scale, utilizing silicon nitride platform. A path for full heterogeneous integration of an optical frequency synthesizer has been demonstrated in a testbed environment, although requiring a silica microresonator on a pedestal accessed by a tapered fiber. However, one of the serious drawbacks in all of these reports is the use of silicon nitride that is fabricated with a complex low-pressure chemical vapor deposition (LPCVD) technique, to avoid cracks in thick films which is required for obtaining anomalous dispersion. The LPCVD also uses high processing temperature, >700 °C, which is unlike plasma enhance chemical vapor deposition (PECVD) based silicon nitride, not compatible with CMOS electronics as the electronics cannot withstand such a high temperature. Furthermore, heterogeneous integration of a synthesizer with LPCVD silicon nitride, lithium niobate based second harmonic generator, III–V based CW lasers and silica pedestal resonator poses a significant challenge, even if one day fully integrated, for high yield and mass production.

Therefore, the mass production of an optical frequency synthesizer is favored with a fully CMOS compatible platform based on silicon photonics which can easily be co-integrated with CMOS electronics. Silicon allows small footprint, high fabrication yield, and low packaging cost. Silicon is a well-established photonics material with superior linear and nonlinear optical properties that have been used for efficient four wave mixing, octave spanning supercontinuum, second harmonic generation, single photon generation and lasing. High nonlinearity and ease in engineering of the dispersion allows silicon to generate octave spanning supercontinuum at energies reaching as low as 4pJ with ≈100 fs pulses, as well as efficient periodically poled second harmonics spanning 100s of nanometers, which is unprecedented. In this work, we utilize these excellent properties of silicon to demonstrate a silicon-photonics based optical frequency synthesizer. We show telecom band, tunable, frequency synthesis with instability of 1 × 10⁻¹² at 1 s level, and 1 × 10⁻¹³ at 10 s level.

2. Results

The frequency of an unknown light wave (viz. a continuous wave (CW) laser) in an optical comb system (clockwork) is given as \( f_{\text{comb}} = N f_{\text{rep}} \pm f_{\text{ceo}} \pm f_{\text{beat}} \) where, \( N, f_{\text{rep}}, f_{\text{ceo}}, f_{\text{beat}} \) are the mode number, repetition frequency, carrier envelop offset frequency of a mode locked laser, and the beat frequency between the CW laser and the mode-locked laser (MLL) comb, respectively. To know the \( f_{\text{ceo}} \) one needs to know all the other terms. In the following section, we describe how all these frequencies are measured with our testbed implementation of the synthesizer, which is shown in Figure 1b along with a conceptual rendering of the entire device (Figure 1a) producing synthesized optical signal and the frequency combs that are phase coherently locked to an electronic reference.

In the experiment, we have used a commercial mode-locked laser as a source with \( f_{\text{rep}} = 200 \text{ MHz} \) and pulse width \(<100 \text{ fs} \) (our progress toward fully integrated mode-locked laser with the recent Q-switched mode locking results (55) is discussed in discussion section). As shown in Figure 1b the synthesizer contains three locking circuitry for \( f_{\text{rep}}, f_{\text{ceo}} \) and CW-to-comb detection and locking. For \( f_{\text{beat}} \) detection, a fraction of the MLL signal is directed toward a photodiode (Figure 1b) where we detect the 5th harmonic of the MLL which is then compared, in the \( f_{\text{beat}} \) locking circuitry, with a radio frequency synthesizer to generate a phase error signal with respect to the reference microwave frequency (10 MHz), which is then fed back to the MLL piezoelectric transducer (PZT) for \( f_{\text{beat}} \) locking.

To detect \( f_{\text{rep}} \) we use self-referencing scheme. As shown in the photonics arm of Figure 1b, the MLL pulses are launched into a silicon rib waveguide with the coupled energy of less than 20 pJ for soliton fission based octave spanning supercontinuum (SC) generation. The spectrum is shown in Figure 2a with \( f \) at 2.3 µm and \( 2f \) at 1.15 µm having on-chip power of -37 and -25 dBm nm⁻¹, respectively. The \( s \) signal is filtered out of the SC and is launched into a silicon waveguide in which a dc electric field is periodically applied along the length to induce a periodic second order nonlinear effect for quasi-phase matched second harmonic generation (SHG). The electric field (26 V µm⁻¹) is applied across the waveguide every 1770 nm (beat length) to achieve a conversion efficiency of 13%/W (16). The length, width and the slab thickness of the waveguide are 1.5 cm, 800 nm, and 100 nm, respectively. The experimental and the simulated SHG signals are shown in Figure 2c. The asymmetry in the spectrum is largely due to the presence of the self-phase-modulation and the strong effect of the dispersion on the pump signal, mainly the 2nd and the 3rd order dispersion. The simulations, performed with Runge–Kutta and split step method, predict that the cross phase modulation of the \( 2f \) due to the pump weakly blue shifts the \( 2f \) by ≈1 nm. The group velocity mismatch (GVM)
between $f$ and $2f$ reduces the temporal overlap between the two signals causing reduction in the bandwidth of the $2f$ signal.\[55\] The GV curve for the SHG waveguide is shown in Figure 2d. By lowering the GVM the bandwidth of the $2f$ signal can be significantly increased, that is because of a broader phase matching between the $f$ and the $2f$ signal.\[51\] The up-converted $2f$ signal and the $2f$ part of the SC signal are combined with a 3 dB coupler and mixed in a balanced photodetector (BPD), which helps increasing the strength of the $f_{ceo}$ while suppressing that of the $f_{2f}$ by up to $>20$ dB. The $f_{ceo}$ signal along with frequency instability measurement is shown in Figure 3a,b. A tunable delay line (TDL) is used in one of the $2f$ arms to ensure maximum temporal overlap of the two $2f$ pulses so as to maximize the SNR of the $f_{ceo}$. A delay line was required in the testbed due to the inherent large configuration of the testbed with devices located separately on different test setups with long free space and fiber interconnections leading to a large delay between the two $2f$ arms. A fully integrated synthesizer, however, will not require a tunable delay line because all of the individual devices will be within a few hundred micrometer range from one another, thus also avoiding inherent chirp, which is accumulated with the free space setups and the delay line that undermines $f_{ceo}$ strength. As shown in the simulated spectrogram of the supercontinuum, Figure 2b, the $f$ and the $2f$ signals are roughly one picosecond apart at the end of the SC waveguide which is almost negligible and can be compensated for with a short silicon waveguide designed for appropriate group velocities for the $f$ and the $2f$ so that they temporally overlap efficiently at the detector.

To generate optical frequencies for a synthesizer we use an integrated erbium-doped tunable ring laser. There are several
advantages of using a laser gain based on rare-earth materials, viz not only are they more economical to produce compared to semiconductor lasers, which require expensive flip-chip and wafer-level bonding,\textsuperscript{[56]} they also readily offer low noise narrow linewidth signals (in kilohertz range, without external stabilization),\textsuperscript{[57-61]} whereas the semiconductor lasers suffer from thermal instability, carrier density fluctuations and non-linear absorption (20x of silicon),\textsuperscript{[62,63]} leading to megahertz level linewidths. However, progress is being made with external cavity very quality filters to narrow the linewidth,\textsuperscript{[64]} reducing frequency instability significantly using fluoride glass resonators.\textsuperscript{[65,66]} We fabricated the tunable laser by depositing erbium-doped aluminum oxide (Al\textsubscript{2}O\textsubscript{3}:Er\textsuperscript{3+}) on a silicon nitride waveguide, fabricated with the plasma enhanced chemical vapor deposition (PECVD) technique compatible with the CMOS electronics, that operates in the C-band and has a linewidth of 340 kHz.\textsuperscript{[61]} As is shown in the photonics arm of Figure 1b, a fraction of the signal from the CW laser is beat with the C-band signal of the SC from the silicon waveguide. The generated phase error signal from the control electronics (CW-comb lock circuitry) is fed to the integrated heater to stabilize the CW laser which has a response time of \(\approx 30\) ps. The spectral range of the laser tuning along with the lasing signal with an on-chip power of \(\approx 250\) \(\mu\)W is shown in Figure 3c. The on-chip and off-chip power was limited by the un-optimized gain doping parameters and the lack of inverse tapers which has been used to demonstrate up to 75 mW of output power which will be implemented in future devices.\textsuperscript{[58]}

The absolute frequency instability was determined using an external, out-of-loop, reference comb (for in-loop measurements\textsuperscript{[67]}), based on a highly nonlinear fiber (HNLF) which was also locked to a common microwave reference and beat with the tunable laser on a BPD in the electronics arm as shown in Figure 1b. The frequency instability of the beat between the silicon-comb stabilized CW laser and the reference comb for three different frequencies are shown in Figure 3d, and the respective time domain data is shown in Figure 4. We must note that the laser is continuously tunable over 20 nm when all the heaters are operating, while within 2.5 GHz continuous tuning can be achieved using only the gain cavity heater.\textsuperscript{[61,68]} We achieved frequency instability of \(1 \times 10^{-12}\) @ 1 s level, comparable to a commercial bench-top system. The slope improves to 1/\(\tau\) by averaging the data at various gate times in the frequency counter. We note that the laser tuning range is kept limited due to a combination of unavoidable high coupling losses of the SC (\(\approx 12\) dB) from the use of free space optics and coupling lenses from chips to fibers, and the thermal fluctuations of the CW laser due to the mechanical vibration from the end-fire coupling of the pump with lensed fibers which compromised the locking strength. To confirm that, we used SC signal from a commercial HNLF comb having similar power level in the telecom band as from the silicon chip and demonstrated a tight lock, enabling a 20 nm tuning range in the C-band, see the Supporting Information. In an all integrated system, the free space coupling losses and the thermal fluctuations of the CW laser will not be present thus full tuning can be achieved over the entire C-band. Further improvement is expected with

Figure 2. Nonlinear signal generation in silicon. a) SC spectrum (experimental), and b) the spectrogram (simulated). c) Experimental and simulated (dashed) second harmonic signal. d) Simulated group velocity curve of the SHG waveguide.
Figure 3. f_{ceo} detection and the frequency instability measurement. a) f_{ceo} signal with a resolution bandwidth 100 KHz. b) f_{ceo} instability (in-loop). c) The normalized tunable CW laser spectrum. d) The out of loop frequency instability of the synthesizer measured at different frequencies. Data taken with (dash) and without (solid) averaging at the individual gate time of the frequency counter.

3. Discussion

It is obvious that full integration will reduce the overall power requirement and will facilitate stronger signal generation especially in the optical frequency synthesis range, i.e., the C-band. Below we discuss how further improvement in the SC and the SHG can be obtained, together with our progress toward fully integrated modelocked laser.

3.1. Optimizing SC and SHG

In this work we utilized a uniform supercontinuum waveguide. By employing a varying dispersion along the length of an SC waveguide one can enhance the supercontinuum selectively for important wavelength window\(^{[47]}\). We have shown recently up to 16 dB enhancement experimentally in the C-band and 100 nm of wavelength extension at the long wavelengths using cascaded waveguide. We also explored three section cascaded waveguide with optimized waveguide length of merely 3 mm for enhancing all three critical wavelength windows (f, 2f and C-band). Tapered waveguides were also explored and they tend to maintain coherence over the entire SC with a long pump pulse, thus relaxing the short pump pulse requirement for a synthesizer. We believe such a device can make the silicon based optical frequency synthesizer more efficient. We note that the SC pumped at 1.9 µm is limited by the TPA (≈0.25 cm per GW), which can be reduced further by pumping with a holmium based laser at longer wavelength.

As mentioned before, the second harmonic generator used in this work was not dispersion engineered for group velocity matching of the pump and the signal, thus allowing only a narrow bandwidth signal generation. Since we have a short pulse at f in the supercontinuum (<100 fs) which is launched into the SHG waveguide, a broad SHG without compromising the efficiency can be obtained by matching the group velocities of the signals at f and 2f, which will help increase the f_{ceo} signal to noise ratio thus facilitating strong stabilization of the octave.

a larger locking feedback bandwidth (currently sub-100 Hz).

To cover even a larger frequency synthesis bandwidth several CW lasers can be integrated on a single platform to be locked to a stabilized comb. Finally, the mode number, N, of the MLL is measured using a technique in which f_{rep} is slightly varied multiple times (in proportion to the CW laser linewidth).\(^{[68,69]}\) We measured N with an error much better than ±0.5 (which will improve to <±0.02 with an all integrated system), thus acquiring knowledge of the exact value of the light wave frequency.
which is used for mode guiding in the gain section and as a Kerr
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spanning comb. Moreover, obtaining a broadband SHG with silicon is relatively easier compared to a more conventional material such as lithium niobate. That is because of the well-established CMOS foundry and the high refractive index contrast in silicon, offering a greater control over the group velocities with dispersion engineering of a waveguide for the same or even different optical modes of the pump and the signal.\(^{53}\)

3.2. Integrated MLL

In this work, we have used a commercial fiber modelocked laser instead of an integrated modelocked laser. We have shown recently fully integrated modelocked laser with integrated gain, reflectors and saturable absorber, a nonlinear interferometer (NLI), on a silicon photonics platform.\(^{55}\) We have achieved 9 mW of average power with 250 fs pulse width at 1.9 µm. Currently, however, the performance of the integrated MLL is limited due mainly to the high losses (\(\approx 1 \text{ dB cm}^{-1}\)) of the silicon nitride waveguide, which is used for mode guiding in the gain section and as a Kerr based saturable absorber, leading to the Q-switching modelocking operation which is unsuitable for optical frequency synthesizer due to high timing jitter of the pulses. The Q-switching instability can be avoided by using a low loss silicon nitride waveguide (\(\approx 0.1 \text{ dB cm}^{-1}\)) which is now readily available from several commercial foundries, such as for LPCVD silicon nitride Ligentec (Switzerland) and Lionix (Netherlands), and for PECVD silicon nitride CNSE Suny (USA) with losses reaching \(< 0.4 \text{ dB cm}^{-1}\).

Also, the integrated saturable absorber's parameters can be adjusted for a given saturable absorption strength while reducing the total propagation loss. Moreover, the availability of high gain medium (\(20 \text{ dB cm}^{-1}\)) with atomic layer deposition of rare earth doped aluminum oxide the requirement of low loss silicon nitride waveguides can be relaxed.\(^{70}\) The pump laser for the modelocked laser will be packaged with the synthesizer in an all integrated system for realizing the desired compact device shown in Figure 1a.\(^{71,72}\)

In conclusion, we have demonstrated a silicon photonics based optical frequency synthesizer in the telecom-band by utilizing the strong third order optical nonlinear effect of silicon to generate an efficient octave spanning supercontinuum and an electric field induced second harmonic. The frequency instability achieved is comparable to a bench-top system. Further improvements can be achieved by increasing the bandwidth of the SHG while maintaining the conversion efficiency with the help of group velocity matched \(f\) and \(2f\) signal, and designing supercontinuum waveguides for selective signal enhancement of the relevant wavelength windows (viz. \(f\), \(2f\) and C-band), by longitudinally varying the dispersion.\(^{47}\) An integrated mode-locked laser will be implemented in the future all-on-chip CMOS based optical frequency synthesizers.\(^{52,53}\)

4. Experimental Section

Device Design and Fabrication: The cross-section of the supercontinuum (SC) waveguide was chosen to enhance the key spectral windows of the supercontinuum viz. \(f\), \(2f\) and the C-band by carefully modifying the waveguide dimension to optimize the third order dispersion.\(^{46}\) The supercontinuum generation was simulated by numerically solving a generalized nonlinear Schrodinger equation (NLSE) using an adaptive split step method. Up to 8th order dispersion coefficients were included along with free carrier dynamics, which showed negligible absorptions at a repetition rate \(< 600 \text{ MHz}\) of the pump pulses.\(^{46}\) To simulate the second harmonic generation, coupled mode equations were solved using the Runge–Kutta and the split-step method. Up to 5th order dispersion coefficients were included in the simulation.\(^{51}\)

The silicon waveguides were fabricated within a 300nm line, in a standard CMOS facility (CNSE, SUNY, Albany) by epitaxially growing silicon to a thickness of 380 nm on a 220nm SOI wafer which was chemically and mechanically polished to reduce roughness. The 193 nm deep-ultraviolet immersion lithography the wafer was then exposed and patterned, and subsequently partially etched down to the target 315 nm, using reactive-ion etching to obtain the desired rib waveguides. The SC and the SHG waveguides in this work have different slab thicknesses, which can be made the same by simply adjusting the beat length in the SHG waveguide. Arsenic and boron difluoride implants were used to form the \(p-i-n\) junction in the SHG waveguide and were connected to the contact pads through the highly doped \(n\) – and \(p\) regions, tungsten vias, and the copper routing layer. The CW laser was fabricated by growing the silicon nitride (SiN) layer on top of a 6 µm thick SiO₂ layer over a 220 nm silicon layer. Both layers were grown with the PECVD. Patterning was performed with the reactive-ion etching as above. The \(\text{Al}_2\text{O}_3\cdot\text{Er}^{3+}\) gain
layer was sputtered over a thin SiN layer at a substrate temperature of 
<400 °C, with the temperature requirement reaching down to 250 °C, fully compatible with the back end of line CMOS process.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N.S. designed, testbed setup. N.S. took the data of the SC and the SHG. N.S. and M.X. supervised and were the principal investigators of the project. All authors contributed to the preparation of the manuscript.

Keywords

silicon photonics, frequency combs, frequency synthesizer, nonlinear photonics

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