Towards CW modelocked laser on chip – a large mode area and NLI for stretched pulse mode locking

NEETESH SINGH,1,2,* ERICH IPPEN,2 AND FRANZ X. KÄRTNER1

1Centre for Free Electron Laser Science (CFEL)-DESY and University of Hamburg, Notkestrasse 85, 22607 Hamburg, Germany
2Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
*neetesh.singh@cfel.de

Abstract: Integrated modelocked lasers with high power are of utmost importance for next generation optical systems that can be field-deployable and mass produced. Here we study fully integrated modelocked laser designs that have the potential to generate ultrashort, high power, and high quality pulses. We explore a large mode area laser for high power pulse generation and study the various mode-locking regimes of dispersion managed soliton pulses in net anomalous and net normal dispersion cavities. Furthermore, we study numerically and experimentally general properties and tunability of a fast integrated saturable absorber based on low loss silicon nitride nonlinear interferometer. We believe this work guides the exploration of the future for integrated high power modelocked lasers.

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1. Introduction

Modelocked lasers (MLL) are a driving force behind many of the optical technologies such as nonlinear optical signal generation [1–4], optical frequency synthesis and broadband coherent communication [5–8], microwave signal generation [9], optical atomic clocks [10], photonic analog to digital conversion [11], astrocomb [12], volumetric 3D data storage [13], laser surgery [14], timing synchronization of high energy accelerator sources [15,16], and many more. These are possible because a rare-earth gain based MLL produces ultrashort and high peak power optical pulses with low timing jitter [17,18].

Passive MLLs have existed in fiber and bulk media for a very long time [19–26]. For the next generation systems, however, integration of the high peak power modelocked laser is important. Here, building up on previous demonstrations [27–30], we show proof of concept designs for integrated MLLs that can generate high peak power pulses with sub 100fs, at high repetition rate (>1 GHz) and sub-100 fs with kilowatt peak power with sub-GHz cavity. Such an oscillator generating high peak power femtosecond pulses will have low pulse to pulse timing jitter [17], which are yet to be demonstrated on an integrated platform, for example electrically pumped semiconductor lasers normally produce very low peak power pulses [31,32]. Although, a rare earth doped MLL is optically pumped, with the advance in bonding, coupling and packaging technology recently a pump diode can be packaged together with an MLL chip maintaining a small form factor of the entire device [33]. The lasers discussed in this work are mainly at telecom wavelength using erbium doped aluminum oxide, but they can easily be adapted to any other rare-earth ions. In the second section we discuss the design for a laser cavity with large lasing mode area (50 µm²) that facilitates increased power in the pulses as well as insusceptibility to optical nonlinearity based pulse instability. Unlike the high power lasers, these designs support only large fundamental modes and thus avoid loss of power to higher order modes. These structures allow seamless transition of fundamental mode from a weak confinement to a high

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confinement region in a single layer thus allowing compact bends and dispersion management while leveraging waveguide nonlinearity. In the third section we discuss pulse generation in net anomalous and net normal dispersion cavity using integrated saturable absorber based on a nonlinear interferometer (NLI). In this section we mainly study high repetition rate erbium laser (>1 GHz), due to its relevance for telecom applications, followed by an investigation on a longer cavity laser (repetition rate ~ 470 MHz) with both erbium (1.55 µm) and thulium gain (1.9 µm) to generate ultra-short very high peak power pulses. The NLI is studied numerically and experimentally in the following section. The tunability of the reflection curve of an NLI using integrated heaters not only compensates for the fabrication tolerances, but more importantly gives an additional degree of freedom in modifying the saturable absorption strength, unlike a semiconductor saturable absorber. That can be useful for, self-starting, suppressing Q-switching instability, and varying the maximum allowed pulse power of an MLL (based on fiber, free space or integrated platform), which is normally fixed in a fiber or free space MLL based on nonlinear interferometer. Such an integrated NLI based saturable absorber will also find applications in Mid-IR modelocked lasers where reliable fast saturable absorbers do not exist [34], especially NLIs based on silicon will be useful as silicon is transparent up to 8 µm.

2. Large mode area

For high power fiber lasers it is customary to use large mode area fiber because it helps to reduce instability in the lasing mode by lowering the intensity and therefore the optical nonlinearity in the medium. A large mode area in the gain region also increases the saturation power to allow lasing with high power [35,36]. For higher power integrated lasers, not only a large mode area is required but seamless transition of the optical mode between the gain (weak confinement) and the guiding (tight confinement) section is desirable to leverage several functionality offered by integrated photonics. Such a device remains largely unexplored in integrated lasers [37–44]. In this proof of concept work we show waveguide designs on integrated platforms that support modes of area up to 50 µm² at 1550 nm, with >95% overlap between the pump and the signal, and offer tight mode confinement with single layer silicon nitride. Here, we design the cavity for in-band pumping (1480 nm), but 980 nm can very well be implemented with slight modification of the waveguide dimensions. Moreover, these waveguides only support fundamental mode thus avoid loss of power to higher order modes that usually plague fiber lasers, and therefore promise high power and high quality of the lasing mode [36].

Two different waveguide designs are investigated as shown in Fig. 1. In Fig. 1(a), the waveguide was designed with a silicon nitride (SiN) layer having the width (w) of 485 nm, height (h) of 800 nm and a silica buffer layer on top (g) of height of 450 nm. The aluminum oxide gain layer thickness is 2.2 µm. The transverse electric (TE) mode profile at 1480 nm (pump), which was calculated using a finite difference based mode solver (Lumerical), is shown in Fig. 1(a). The effective area of the mode at the pump wavelength is ~ 50 µm². The energy confined in the gain layer is ~ 98%. The pump and signal overlap is over 98%. The advantage of this waveguide design is that gain layer can either be directly deposited on the smooth top surface of the device directly out of the foundry, or can be bonded with a standalone gain medium, like a very thin semiconductor gain medium, thus significantly lowering the propagation loss as it doesn’t require any additional etching. Also this device does not require a relatively thicker (several microns) gain layer. Moreover, the modes can be pulled into the SiN layer very rapidly and can be fully confined in the SiN waveguide by increasing its width, thus offering transition between different sections, such as gain to saturable absorber or external cavity, without suffering from reflections due to index mismatch. Any spurious reflection becomes detrimental for the stability of the lasing modes thus making an MLL highly sensitive to these reflections [45,46]. The mode can be switched from the gain medium to the SiN layer by increasing the SiN width by >45 nm (<100 nm for 1550 nm signal) which can be achieved adiabatically within a few microns length,
as shown in Fig. 1(a1, a2 and a3). For shorter wavelengths the transition speed increases, for example at 980 nm the width change required is merely 15-25 nm [as shown in Fig. 1(c1, c2 and c3)], for a buffer layer of 200 nm. The range of SiN width change required narrows down with thicker buffer layer making it more sensitive to fabrication tolerances. Since the SiN layer is 800 nm thick, it allows anomalous dispersion, with an increased width of the SiN layer, in the telecom window therefore supporting optical nonlinear functionality, such as supercontinuum generation, as well as dispersion compensation which is required in a modelocked laser. Such a device does not require different vertical layers of SiN for mode transitions, tailored to different functions, which is prone to unwanted reflections due to optical impedance mismatch between the different layers at the transition region [47–49], which, as mentioned above, can be detrimental in a laser. Such a device relies on the refractive index of the SiN being higher than the gain layer which is higher than the oxide layer. We have also shown in Figs. 1(a4) and 1(c4), the 1550 nm lasing signal mode profile with >97% mode overlap with the pump.

Fig. 1. a) Large mode area waveguide with gain above a buffer layer of thickness $g$. a1) Mode profile of 1480 nm with 50 $\mu$m$^2$ mode area. a2) and a3) modes with wider SiN demonstrating fast mode transition. a4) Mode profile at 1.55 $\mu$m of the waveguide in (a1). Here, $t = 2.2 \mu$m, $g = 0.45 \mu$m, $h = 800$nm. b) Large mode area with direct deposition of gain on SiN. b1) Mode profile at 1480 nm of area $\sim 50\mu$m$^2$. b2) and b3) Mode profiles with wider SiN. b4) Mode profile at 1.55 $\mu$m of the waveguide in (b1). Here $t = 3.2 \mu$m, $w = 0.2 \mu$m, and $h = 0.4 \mu$m. c1) Buffer waveguide (a) mode profile at 0.98 $\mu$m of area $>50 \mu$m$^2$. c2) and c3) Mode profiles with wider SiN. c4) Mode profile at 1.55 $\mu$m of the waveguide in (c1). Here $t = 2.2 \mu$m, $g = 0.2 \mu$m, $h = 800$ nm.
Another design investigated is shown in Fig. 1(b), where there is no buffer layer and the gain is deposited directly on top of the SiN waveguide. The width of the SiN waveguide is 200 nm, the thickness is 400 nm and the aluminum oxide layer is 3.2 µm thick. The calculated mode area is $\sim 50 \, \mu m^2$ for the pump and the overlap between the signal and the pump is over 95%. A similar device has been used previously although with mode area of roughly $5 \, \mu m^2$ [28]. An efficient mode overlap of the signal at 1.55 µm with shorter wavelengths such as 980 nm pump wavelength can be obtained, as is expected, by reducing the thickness of the SiN layer while maintaining a large mode area (not shown). The advantage of this device over the previous one, in Fig. 1(a), is that it does not require a thick SiN layer, and requires less modification in the design for varying mode sizes, while also offering full signal mode confinement within the same SiN layer by increasing the width over 1000 nm. We must note that in this design we have not included the pedestal above the aluminum oxide layer which would be present after the deposition on top of the SiN waveguide (which modifies the mode area), as it can be easily polished away. We also emphasize that in both of the designs even larger mode area can be obtained ($\sim 100 \, \mu m^2$), and due to tight confinement with increased SiN width, compact bends can be implemented in the laser to allow multiple straight gain sections.

3. Modelocked laser

In this section we present designs of integrated modelocked lasers based on net anomalous and net normal dispersion cavity [50–53]. We simulate a linear cavity due to the lack of a reliable isolator required for a ring cavity, which makes the system more sensitive to reflection and spatial hole burning but it has the advantage of ease in fabrication. In the simulation, we do not take into account spatial hole burning [54,55] and reflection based instabilities [56].

In this model we solve for the pulse evolution in a cavity composed of different sections as shown in Fig. 2 where the pulse energy, peak power and spectrum changes in different sections in a stretched pulse cavity [57], as discussed later. Here, the DCM (double chirped mirror) is an apodised chirped grating that provides the required dispersion [58–60], the gain is based on rare earth doped Al₂O₃, the passive section is made of a low loss waveguide for attaining desired cavity length, and the NLI (nonlinear interferometer) is an intensity dependent interferometric reflector [61] acting as a saturable absorber (SA); more on the NLI in section 4 (readers interested in NLI can go straight to section 4). We note that the gain section here can replace the passive section with the gain adjusted such that the total roundtrip gain remains the same. The nonlinear Schrödinger equation (NLSE) for the pulse evolution in the cavity is given as:

$$\frac{\partial E}{\partial z} = \left[ \frac{g - \alpha}{2} + \left( D_k - \frac{\beta_2}{2} \right) \frac{\partial^2}{\partial t^2} + \frac{\beta_3}{6} \frac{\partial^3}{\partial t^3} - j\gamma |E|^2 \right] E$$  \hspace{1cm} (1)

Here, $E$ is the pulse field envelop evolving along the length of the cavity. The NLI, a nonlinear Michelson type interferometer, is made of two arms attached to a coupler acting as a beam splitter with power split ratio of $r$ and $1-r$ in reflection and transmission, respectively, see section 4. We have used $r$ between 0.8 and 0.75. When the pulse enters the NLI the electric field in the high power arm is $E_h = \sqrt{r}E$, and in the low power arm is $E_l = i\sqrt{1-r}E$. After traversing the NLI, when the pulse returns back to the cavity the field envelope is given as, $E = \sqrt{r}E_h + i\sqrt{1-r}E_l$, and the signal out of the cavity from the NLI is given as, $E_o = i\sqrt{1-r}E_h + \sqrt{r}E_l$, which is the output of the laser in the configuration studied in this work. Similarly, a nonlinear optical loop mirror (NOLM) or nonlinear amplifying loop mirror (NALM) can be implemented if required. The gain $g = g_0/(1 + P_{avg}/P_{sat})$ where $g_0$ is the small signal net gain and the $P_{avg}$ is the average power in the cavity, and the saturation power, $P_{sat} = E_{sat}^2/\gamma_0$. The $\gamma_0$ is the gain life time and the saturation energy, $E_{sat} = A_{eff} hf/(\epsilon_0 + a_c)$ where $A_{eff}$ is the effective area of the lasing mode, $hf$ is the signal photon energy, and $\epsilon_c$ and $a_c$ are the emission and absorption cross-sections of the signal, respectively. In steady state, when the gain is saturated, $P_{avg} = P_{sat}(g_0/\gamma_0 - 1)$, where $\gamma_0$ is a
function of the passive loss ($\alpha$), the dispersion due to the gain ($D_g$) and the cavity ($\beta_n$) [50]. For a CW narrow linewidth laser $l$ is simply $\alpha$. Usually for high power lasers high $P_{sat}$, that is high $P_{sat}$ and $g_o$, is required. As the net gain is limited by the amplified spontaneous emission (unless multi-stage gain is used), $P_{sat}$ can be increased by increasing the $A_{eff}$ while utilizing long gain life time which is required for low noise lasers. In the simulation, the gain, which is proportional to the pump power, is used such that the signal average power remains between 10–40 mW, which is similar to the experiment where over 50 mW intracavity power has been obtained [28]. The gain dispersion, $D_g = g/(2\pi\Omega)^2$, where $\Omega$ is the gain bandwidth (for $\text{Al}_2\text{O}_3: \text{Er}^{3+}$ it is 4 THz). The background loss $\alpha$ is 0.1 dB/cm. The nonlinearity, $\gamma = 2\pi(n_2)/\lambda A_{eff}$, where $n_2$ is the Kerr factor which is different for different sections of the cavity.

The nonlinearity ($\gamma$) should be low for the gain and the passive section to avoid pulse instability [50,62], that is because higher nonlinearity causes the competing weak pulses to have enough peak power to experience less loss through the SA (this weak long pulse is also referred to as the continuum interchangeably in the rest of the paper). Unless large dispersion is used to spread the weak continuum pulses in time they start to rob gain from the main pulse and eventually destabilize it after several roundtrips. For the simulation standard split-step Fourier method is used with a window size of 88 ps and a grid size of 2.7 fs. In all the simulations presented here, there was no initial noise added as the effect of the noise was negligible as was seen in the simulations (not shown).

3.1. Net anomalous cavity

Here, we simulate a cavity with a negative net group delay dispersion (GDD), such as the one shown in Fig. 3. In this we used the length of the gain section as 20 mm, passive section as 40 mm, NLI arms as 10 mm, resulting in a repetition rate of 1.38 GHz. The $\sigma_c$ and $\sigma_e$, are $5.3 \times 10^{-25}$ m$^2$ and $3 \times 10^{-25}$ m$^2$ with $t$ being 3 ms. The $A_{eff}$ of the mode in the gain and the passive section is 50 $\mu$m$^2$ and in the NLI it is 0.66 $\mu$m$^2$. The NLI power split ratio is 80:20. The Kerr factor for the SiN = $3 \times 10^{-19}$ m$^2$/W, Al$_2$O$_3$ and SiO$_2$ = $3 \times 10^{-20}$ m$^2$/W. The dispersion in the gain is $\beta_{2g} = -1.51 \times 10^{-26}$ s$^2$/m and $\beta_{3g} = 1.98 \times 10^{-40}$ s$^3$/m, in the passive it is $\beta_{2p} = 1.94 \times 10^{-25}$ s$^2$/m and $\beta_{3p} = 2.14 \times 10^{-39}$ s$^3$/m, and in the NLI it is $\beta_{2n} = 1.50 \times 10^{-24}$ s$^2$/m and $\beta_{3n} = -5.33 \times 10^{-39}$ s$^3$/m. The dispersion of the DCM is adjusted to get the desired net anomalous dispersion. For the simulation the initial signal peak power was sub-femtowatt and the pulse (sech) width was 10 ps. In Fig. 3(a) we show the spectrum of stable pulses after 1000 roundtrips in a cavity with the net GDD of $-430 \times 10^3$ fs$^2$. The average power of the stable pulses was 13 mW (observed at Passive (backward) at position 4 in Fig. 2). We see the spectrum is similar at various locations in the cavity that is because the bandwidth of the pulse is narrow enough to avoid gain filtering. The Kelly sidebands appear, as expected for large net anomalous cavity, because the pulse experiences modulation of the nonlinear term $\gamma|E|^2$ [Eq. (1)], through the cavity [63]. The peak power evolution of the pulse at different locations in the cavity is shown in Fig. 3(b). For the stable pulses the power is higher after the gain and drops slightly after the passive section due to the
background loss and drops significantly in the NLI as the intensity dependent reflection is 40% at this peak power level (more in the NLI section), which is further reduced in the passive section due to propagation loss.

\[ \text{Fig. 3. Pulse evolution for the net GDD of } -430k \text{ fs}^2 \text{ (k is } 10^3). \]

- a) The pulse spectrum at various points in the cavity. Passive (forward) - after passive and before the NLI section (at 2 in Fig. 2), After gain - before the passive section (at 1 in Fig. 2) After NLI - before the passive section (at 3 in Fig. 2), and Passive (backward) - after passive and before the gain (at 4 in Fig. 2). After NLI and Passive (backward) spectra almost overlap, and Passive (forward) and After Gain spectra almost overlap.
- b) Evolution of the peak power of the pulse.
- c) and d) Evolution of the pulse in wavelength and time domain for 1000 iteration (monitored After NLI).

In Fig. 3(c) the spectral evolution of the pulse is shown where the sidebands start appearing well before 100 iterations and reach full stability under 500 iterations, just like in the time domain shown in Fig. 3(d). Next, we show how the pulse evolves for varying net anomalous GDD. In Fig. 4(a) the stable pulse spectra (After NLI, at position 3 in Fig. 2) for net GDD ranging from \(-55 \times 10^3\) to \(-455 \times 10^3\) fs\(^2\) is shown. Here the pump power thus the gain was adjusted for higher average power (around 40 mW, at location 4 in Fig. 2), which helps stabilizing the pulses for lower net anomalous GDD, therefore producing shorter pulses. As the net GDD is lowered the pulse starts getting broader in spectrum, the peak power increases, and also the Kelly sidebands start to weaken and eventually disappear near zero net GDD (see net normal cavity section). The pulse does not stabilize in this configuration at or below the net GDD of \(-35 \times 10^3\) fs\(^2\) unless the pump power or the self-amplitude-modulation (SAM) of the NLI, i.e. the strength of the saturable absorber, is increased. As mentioned before, as the net GDD is reduced the susceptibility of the pulse to the weak competing long pulse (continuum) increases, because at lower net GDD the temporal broadening of the weak continuum is reduced causing increase in its peak power thus its higher reflectivity back to the cavity. By increasing the SAM, which is the rate of change
of the reflectivity of the NLI with the peak power, see Section 4, the selectivity for a relatively higher power pulse is increased thus keeping the weak continuum from building up. For a cavity with a fixed saturable absorber, the pump power can also be increased to increase the overall initial pulse power so that the pulse reaches a relatively higher region of SAM of the NLI, which is strongest for a given saturable absorber half-way between its minimum and the maximum reflection point and is zero at these points. Usually a lower SAM value of a saturable absorber in the Kerr based cavity contributes to non-self-starting behavior. By mechanical vibration or active modulation technique in the cavity, the initial pulse gets enough peak power to be in the relatively higher SAM region thus helping it to self-start. The effect of the pump power and the SAM on the self-start issue has been studied in [64–66]. Additionally, the cavity configuration used in this section can be stabilized for a very low net GDD (∼0 fs²) by increasing the SAM for the low power pulses just by applying an external phase bias on an NLI arm (using heaters, see NLI section).

![Fig. 4. a) Pulse spectrum vs net GDD and b) spectrum of the pulse at different locations in the cavity with the net GDD of -55k fs² (k is 10³). Passive (forward) - after passive and before the NLI section (at 2 in Fig. 2), After gain - before the passive section (at 1 in Fig. 2), After NLI - before the passive section (at 3 in Fig. 2), and Passive (backward) - after passive and before the gain (at 4 in Fig. 2). After NLI and Passive (backward) spectra almost overlap, and Passive (forward) and After Gain spectra almost overlap.](image)

In Fig. 4(b), the spectra for a stable pulse for a net cavity GDD of -55k fs² is plotted, having a peak power of 100 W in the gain section. Here we see the spectrum changes significantly at different locations of the cavity (along with the pulse energy, not shown). That is because the gain filtering is strong for such a broadband pulse. The pulse regains its bandwidth in the NLI which allows strong self-phase modulation due to silicon nitride’s high Kerr factor.

In Fig. 5 we plot the output pulse from the NLI (reject port), in time [Fig. 5(a)] and wavelength [Fig. 5(b)] for the net GDD of -55k fs² having a peak power of 20 W and a pulse width of < 1 ps (chirped). The output pulse shape is flatter, in fact having weak shoulders, whereas the pulse back to the cavity is narrower in time. That is because the output is from the rejection port of the NLI which gets the rejected wings of the main pulse thus making the cavity pulse shorter in time, see section 4. Pulses with shape like the one in the cavity can be extracted for the output with an additional drop port anywhere in the cavity while incurring additional loss. The cavity pulse energy is 20 pJ and the output pulse energy is roughly 10 pJ. Since the pulses generated by the MLL is highly chirped, the peak power of the output pulses can be increased by a factor of 2, by removing the chirp (dechirping) from the pulses using a waveguide or a fiber with an appropriate dispersion, to get up to 40 W with a pulse width of 250 fs.
3.2. Net normal cavity

In this section we study an MLL with a net normal GDD. For the simulation we have used similar parameters as in the previous section except the length of the NLI is 22 mm resulting in a pulse repetition rate of 1.15 GHz, the NLI power split ratio is 75:25, and as before the DCM dispersion is varied to obtain a net normal GDD. In Fig. 6(a) we show the spectrum of the stable pulse (after 1000 iteration) at various points in the cavity of net GDD of $110 \times 10^3 \text{fs}^2$. The pulse has some spectral filtering after the gain and gets broad again after the NLI. The shoulders appear in the pulse spectrum as in an all normal dispersion laser [26], and in fibers with self-phase modulation [67,68]. The peak power evolution of the pulse at different locations in the cavity is shown in Fig. 6(b), which follows similar trend to that in Fig. 3(b). The pulse stabilizes faster than with the net negative GDD cavity (Fig. 3), because here the average power in the cavity (at location 4 in Fig. 2) is higher, around 24 mW. Here, we used higher pump power and a stronger NLI because the pulse tends to have lower peak power in the normal dispersion NLI making it harder to modelock the pulses. The spectral and temporal evolution are shown in Figs. 6(c) and 6(d), where we see the pulse reaching stability after close to 200 iterations. In Fig. 7(a) we show the pulse spectra (After NLI, at position 3 in Fig. 2) for different net normal GDD of the cavity. As the net GDD gets more positive the pulse bandwidth starts getting narrower, the peak power reduces, and the shoulder gets stronger. In this configuration to get stable pulses above $110 \text{fs}^2$ one needs to either increase the pump power or the SAM of the NLI. With lower net GDD, as in the net anomalous case, the pulse gets broadband and shorter in time.

Moreover, this device can work in a cavity with dispersion ranging from net normal to net anomalous, as can be seen in Fig. 7(a), where the pulse is stable in the negative (-2k fs$^2$) close to zero net cavity dispersion. That is because the NLI has a higher SAM than in the previous section. The highest intracavity peak power for the net GDD of 0.9k fs$^2$ was 150 W after the gain section. In Fig. 7(b) we show large spectral variation due to the gain filtering (for net GDD of +45k fs$^2$) with roughly 10-15 nm bandwidth narrowing in the gain section. The pulse recovers in bandwidth after the NLI, however, due to high positive chirp in the cavity the peak power remains low. Also, as seen in Fig. 8(a), the pulse at the output of the NLI and the one back to the cavity look very similar. That is because the peak power of the pulse in the NLI is low due to high chirp, and therefore the pulse shortening (shaping) effect of the NLI is not strong.

The cavity pulse energy is 20 pJ (observed at position 3 in Fig. 2) and the output pulse energy is roughly 10 pJ, i.e. the output peak power is 8 W. The output pulse can be dechirped externally to reach up to a peak power of 90 W with an almost 10x linear compression, producing pulses as
Fig. 6. Pulse evolution for the cavity of net GDD of $+110k$ fs$^2$ ($k$ is $10^3$). a) The pulse spectrum at various points in the cavity. Passive (forward) - after passive and before the NLI section (at 2 in Fig. 2), After gain - before the passive section (at 1 in Fig. 2), After NLI - before the passive section (at 3 in Fig. 2), and Passive (backward) - after passive and before the gain (at 4 in Fig. 2). After NLI and Passive (backward) spectra almost overlap, and Passive (forward) and After Gain spectra almost overlap. b) The evolution of the peak power of the pulse. c) and d) The evolution of the pulse in wavelength and time domain for 1000 iteration (After NLI).

Fig. 7. a) Pulse spectrum vs net GDD and b) spectra of the pulse at different location in the cavity with the net GDD of $+45k$ fs$^2$ ($k$ is $10^3$). Passive (forward) - after passive and before the NLI section (at 2 in Fig. 2), After gain - before the passive section (at 1 in Fig. 2), After NLI - before the passive section (at 3 in Fig. 2), and Passive (backward) - after passive and before the gain (at 4 in Fig. 2). After NLI and Passive (backward) spectra almost overlap, and Passive (forward) and After Gain spectra almost overlap.
Fig. 8. a) The spectrum of the output pulse from the NLI reject port (solid blue) and the pulse back to cavity after the NLI (dash). The dechirped output pulse (red) with 90 W peak power and 110 fs pulse width using an smf28 fibre (inset). b) The spectrum of (a). The net GDD of the cavity is 0.9k fs².

short as 110 fs [52]. In the net normal and the net anomalous GDD cavity simulations, to keep the computation time short we used low pump power to keep the average power within 40 mW (at position 4 of Fig. 2). In a real device this can be higher, thus one can achieve higher peak power pulses with shorter pulse widths. Furthermore, the cavity length can also be increased to increase the power in each pulse, which is studied next. And as is routinely done, an external gain section can also be used to amplify pulses, for example with an integrated gain waveguide that can provide high net gain >10 dB [69–72], however, without any reduction in the timing jitter of the pulses.

3.3. Ultra-short high peak power pulses with a longer cavity in erbium and thulium laser

In this section we study high power MLLs. We simulate two different lasers with a longer cavity (21 cm one way) allowing a repetition rate of ~470 MHz. Such a device will have a footprint of <10 mm², given the tight confinement and low loss achievable in silicon photonics [73,74]. For the longer cavity erbium laser operating at 1.55 µm, the passive cavity length of the MLL studied above was increased in order to obtain the desired cavity length with modified grating dispersion to give an overall net GDD close to zero. The NLI properties were also slightly modified to achieve mode locking while avoiding continuum break-in that can easily happen in a cavity having zero net dispersion. The results are shown in Fig. 9 with the intracavity pulse spectrum monitored at different points as per Fig. 2. The spectrum and the pulse width evolves along the length of the cavity as mentioned above. The pulse bandwidth and the energy after the NLI is 50 nm and 120 pJ, respectively. An intracavity peak power of 600 W with a pulse width of 200 fs at an energy of 141 pJ is observed at Passive (forward). The pulse width of the output de-chirped pulse is 100 fs with a peak power of 200 W. Intracavity average power monitored at position 4 in Fig. 2, Passive (backward), is 53 mW.

We also investigated briefly in this section a thulium based integrated MLL operating at 1.9 µm as it offers higher gain, saturation energy, and gain bandwidth (6.5 THz used in the simulation) than an erbium laser at 1.55 µm. Moreover, waveguiding material - silicon nitride, does not suffer from the N-H losses around 1.9 µm, as it does in the telecom window [75], thus a laser operating in this wavelength range need not require low pressure chemical vapour deposition (LPCVD) based silicon nitride fabrication which requires high temperature. The cavity parameters were very similar to the erbium laser with gain parameters taken from Ref. [27]. Since the power in the cavity increases significantly in this laser, to support high power operation the first reflection peak of the NLI (see section 4) is shifted to higher power by adjusting its power split ratio and
effective mode area. The results are shown in Fig. 9. The pulse bandwidth and the energy after the NLI is 80 nm and 270 pJ, respectively. An intracavity peak power of 1550 W with a pulse width of 225 fs at an energy of 370 pJ is observed at Passive (forward). The pulse width of the output dechirped pulse is 65 fs with a peak power of 950 W. Intracavity average power monitored at position 4 in Fig. 2, Passive (backward), is 85 mW. Although not presented, we must note that a thulium laser produces relatively higher power than an erbium laser even with a shorter cavity (> 1 GHz rep. rate), as can be expected.

4. Nonlinear interferometer (NLI) as a saturable absorber

A modelocked laser requires a device that provides higher gain for shorter pulses than for longer pulses. This can be achieved with an intensity sensitive reflector (a saturable absorber) inside the cavity as short pulses tend to have high peak power. An NLI is such a device based on Kerr nonlinearity and optical interference. The idea of shortening a pulse with an interferometric system has been employed in the last few decades using external nonlinear Fabry-Perot interferometers and nonlinear Michelson interferometers [61,76–79]. Kerr based saturable absorbers have been in use for many years with different modelocking schemes. For example Kerr lens modelocking (KLM) based on self focusing has been used to generate pulses as short as 5 fs [25]. Additive pulse mode locking [24,78] relying on a Fabry-Perot based external nonlinear cavity for pulse shortening made modelocking possible with various fiber based systems.
and was extended into many other interfereometric versions based on a nonlinear polarisation rotation (NPR) [80], a nonlinear optical loop mirror (NOLM) [61] and a nonlinear amplyfying loop mirror (NALM) [81]. A Kerr based SA has various advantages over a semiconductor based SA, for example, it tends to produce shorter pulses, has high damage threshold and is broadband. However, it usually causes self-starting issues in an MLL, mainly due to the low SAM at low pulse peak power when the pulse is building up, as has been observed before [66]. In this work we utilize silicon nitride waveguide for a nonlinear Michelson type saturable absorber that can easily be integrated [82], and due to its high nonlineairty compared to a silica fibre it can potentially facilitate self-starting. Additionally, the relative ease in tuning the reflectivity of an NLI using externally applied phase bias (see below), the SAM can be increased which can be useful to help self-start an MLL, and avoiding Q-switching instability at lower pump powers.

In this work we have used a Michelson type nonlinear interferometer as shown in Fig. 10(a) (inset). It is based on a coupler with \( r > 0.5 \), so that one arm has higher power than the other for obtaining a differential power dependent phase shift. Maximum reflection back to the cavity happens when the differential phase shift, \( \Delta \Phi_n + \Delta \Theta = m \pi \), where \( \Delta \Phi_n \) is the nonlinear phase shift difference between the high power arm (\( r \)) and the low power arm (\( 1-r \)), and the \( \Delta \Theta \) is any additional phase shift difference due to fabrication tolerance or externally applied bias (as is discussed later), and \( m \) is an odd integer (for minimum reflection \( m \) is an even integer). The reflection strength cycles through its maxima and minima with the pulse peak power. If \( r = 0.5 \), the \( \Delta \Phi_n \) will be zero thus no light will be reflected (assuming \( \Delta \Theta = 0 \)). To understand the key dynamics of an NLI we have calculated pulse evolution using NLSE, as in Eq. (1) (where the gain is zero). The reflection curve (Reference) shown in Fig. 10(a) was calculated with a 300 fs pulse into the NLI arms of 4 mm length, \( r = 0.8 \), effective area of the mode \( = 0.85 \mu m^2 \), waveguide loss \( = 0.1 \) dB/cm, Kerr factor \( = 3 \times 10^{-19} m^2/W \). With the increase in power the reflectivity back to cavity increases until the differential phase shift reaches \( \pi \). The upward slope, upto the 1\textsuperscript{st} peak, is the region where an NLI is used as a saturable absorber, in the downward slope it is used as a pulse limiter to stabilize pulses [83].

Self-amplitude modualtion (SAM) is the slope of the reflection curve, as shown in Fig. 10(a), which determines the strength of an NLI as a saturable absorber. \( \text{SAM} = \frac{dR}{dP}(1/2 \sqrt{R}) \), where \( R \) is \( E_r/E_{in} \), i.e the ratio of the energy of the reflected and the input pulse, and \( P \) is the input peak power. SAM determines how strongly a pulse of certain peak power will be reflected, hence experience lower loss in the cavity than the weak competing long pulses (continuum). SAM is zero at the maxima and the minima of a reflection curve and peaks where the slope is the strongest. The higher the SAM the stronger the reflectivity of a pulse for a given power compared to the background continuum, thus a larger SAM helps self-starting an MLL. However, as the SAM increases with the pulse power, the laser can go into Q-switching instability [66,84], which can be overcome by increasing the pump power to help raise the pulse peak power to reach the lower SAM region near the 1\textsuperscript{st} reflection maxima, see Fig. 10(a). Also the limit on the maximum power achievable, determined by the 1\textsuperscript{st} reflection peak of an NLI, can be varied to a high or a low power with the help of tunability of the reflection curve by varying external phase bias (\( \Delta \Theta \)) (see below). In the simulation presented in this section we have not included dispersion. With normal dispersion waveguides in an NLI the peak of the reflectivity curve shifts to higher power as the pulse peak power is reduced, and therefore the overall phase-shift is reduced. Anomalous dispersion in an NLI can cause opposite effects along with the soliton effect which has been used for soliton switching [85]. The general trend, however, can be extracted by only including the nonlinear term.

Next, we show the dependence of the NLI’s reflectivity curve on its various parameters. By reducing the effective area (\( A_{eff} \)) the intensity in the NLI is increased thus \( \Delta \Phi_n \) is increased causing the peak to shift to lower power compared to the reference. With higher loss (0.3 dB/cm) the overall curve shifts down (due to high propagation loss) and the peak shifts to higher power.
Fig. 10. a) The NLI reflection curves for different device parameters. Schematic of the NLI (inset), where reflection is the signal back to cavity, $\Phi$ is the nonlinear phase shift, $L$ is the length of the cavity, $r$ is the coupler power splitting factor, $R$ is the reflectivity of each waveguide, using Bragg grating, which is kept 100% in the simulation. $E_r$ and $E_{in}$ are the energies of the reflected and the input pulse. The SAM curve (black dots) is shown for the reflection curve (black solid). b) The pulse in time domain for different powers. $T$ is the output from the NLI, $R$ is the reflection. Dash, dash-dot and solid curves are for 80 W, 250 W, 450 W pulse peak power, respectively. c) The spectrum for the pulses in b). d) The NLI curve for the MLL simulated in section 3.1 and 3.2 for a cavity with the net GDD of -55k fs$^2$ and 0.9k fs$^2$, respectively.

(by 15 W) as more power is required for $\pi$ phase shift. Increasing the length of the NLI to 8 mm affords larger $\Delta \Phi_n$ thus the peak shifts to lower power, but due to higher total propagation loss the peak drops by 0.015% compared to the reference. Also we observe the reflectivity of the 2nd minima and the maxima are different from that of the 1st. That is because, with high peak power the nonlinear phase shift range is large across the width of the pulse, and hence only part of the pulse is transmitted or reflected, which gets even more complicated with dispersion. By increasing the $r$ the reflection peak shifts to lower power as there is more power now in the high power arm giving high $\Delta \Phi_n$, this however reduces the SAM. In Fig. 10(b) we show how the pulse at different peak powers evolves through the NLI [Reference in Fig. 10(a)] in single pass. Signals are normalised to their maximum to clearly see the changes in shape. At low power, with an 80 W pulse (dash curve), the $\Delta \Phi_n$ is small, thus there is a weak pulse shaping effect and all the signal – input, reflected and the output, look similar. As the power is increased to 250 W (dash-dot), there is strong $\Delta \Phi_n$ at the peak of the pulse compared to the sides, hence a large part of the pulse is reflected, and the sides are rejected through the output (a dip at the centre can be seen in the output pulse). This helps shortening the pulse back to the cavity. As the power is increased further, 450 W (solid), a larger part of the pulse acquires nonlinear phase shift, causing
stronger reflection and leaving a larger dip in the middle of the output signal. Here, since we are not using dispersion, pulse shortening is mainly due to nonlinear interference in the NLI and not due to self-phase modulation in the high power arm of the NLI. The corresponding spectra are shown in Fig. 10(c). In Fig. 10(d) we show the NLI reflection curves for the MLL with the net anomalous and net normal dispersion of -55 fs\(^2\) and 0.9 fs\(^2\), studied above in section 3.1 and 3.2. The curves are not only different due to differences in the NLI’s length and the coupler power splitting ratio \(r\), but also due to difference in the pulses entering the NLIs. The difference in the pulse shaping between net anomalous and normal cavity, seen in Fig. 5(a) and Fig. 8(a), is due to the fact that the pulse in the NLI, in net anomalous dispersion cavity, has relatively larger nonlinear phase shift [similar to the high power case in Fig. 10(c)] compared to the one in the net normal cavity [similar to the low power case in Fig. 10(c)]. To increase the pulse shaping in the net normal cavity and also facilitate pulse stability at lower power, a lower or anomalous dispersion of the NLI in the net normal cavity can be used while making sure not too high of anomalous dispersion in the NLI is used as that can cause the competing weak continuum to destabilize the modelocking.

4.1. NLI Measurement

We have designed and tested an NLI made of silicon nitride waveguide fabricated using LPCVD technique. To account for the fabrication tolerance and applying external phase shift bias ∆Θ (see above), heater layers were deposited on top of the waveguides. The length of the waveguides in the NLI is 4 mm, \(r = 0.8\), \(A_{\text{eff}} = 0.85 \mu m^2\), the dispersion \(\beta_2 = -1.25 \times 10^{-25} s^2/m\) and \(\beta_3 = -8.15 \times 10^{-40} s^3/m\), and the waveguide width = 1.1 \(\mu m\) and the thickness = 800 nm. The reflectors at the end of the waveguides were made of loop mirrors. The device was tested with a laser having 200 fs pulses at 80 MHz repetition rate. The output was collected from the NLI’s output (rejection port), as shown in Fig. 11(a), and the data was taken for different heater temperatures. To obtain 0.3 °C and 1 °C temperature changes, corresponding to 0.08π and 0.26π phase shifts, 6 mA and 10 mA currents were applied, respectively. The simulations of the transmission and reflection curves are shown in Figs. 11(b) and 11(c) that also suggest that the fabrication tolerance based phase difference between the two waveguides of the NLI was ∼ 4π which can happen with micron level length variation in fabrication. The peak of the curve moves to high power, see reflection curves, by applying thermal phase shift on the high power arm. We also observe the peak of the reflection is dropping in magnitude with the thermal phase shift. This can be understood by seeing Fig. 11(d). Here, the device was simulated without any fabrication tolerance based or externally applied phase shift, i.e. with 0 °C (an ideal condition). By applying a phase shift of π with 3.9 °C (on the low power arm) the peak of the curve shifts to zero power and also the magnitude of the reflection increases to almost 100%, compared to the 0 °C case of 80%. That is because, near zero power there is almost negligible nonlinear phase shift (∆Φ\(_n\)) across the pulse, from the center to the edges. By applying a constant π phase shift, the total differential phase shift at every point in the pulse becomes almost a π, therefore the entire pulse gets reflected (that of course without any pulse shaping). However, as the peak is shifted to higher power, the pulse does not have negligible phase shift across its width anymore i.e. the peak has significantly higher phase shift than the sides. Therefore, a constant phase shift causes some part of the pulse to be of π and some part to be of different phase, hence only part of the pulse gets reflected back. That is the reason for the reduction in magnitude of the peak of the reflection curve as it shifts to higher power, seen in Fig. 11(c). This suggests that low power pulses of any shape will be reflected more efficiently than high power pulses, which can find applications where close to full reflection/switching is required for low power signal.

Furthermore, the peak of SAM of an NLI can be shifted to be near zero pulse power by applying heating on the low power arm as that shifts the 1\(^{st}\) reflection peak towards lower power. For example, in Fig. 11(d) the reflection curve for 0 °C can be moved to the left towards low
power such that the slope of the curve (SAM) is the strongest near zero pulse peak power. This will be useful, as a higher SAM helps self starting and stabilizing the pulses, especially for a cavity having high nonlinearity and low net GDD, without requiring to modify the length and the coupling ratio (r) of the NLI. Moreover, once the pulse has stabilized near the 1st reflection peak, by applying thermal phase shift on the high power arm the peak of the reflection curve can be shifted slowly to higher power thus increasing the maximum achievable pulse power limit.

5. Conclusion

We have shown designs of large mode area waveguides for integrated modelocked lasers that do not support higher order modes unlike the fibre lasers. We also simulated net normal and net anomalous modelocked laser cavities showing different pulse dynamics similar to what has been seen in the experiments with fiber lasers [51], showing potential for generating high output power and short pulses without any additional amplifier. Furthermore, we studied an integrated nonlinear Michelson interferometer as a fast saturable absorber numerically and experimentally. We believe this work will help the design of the future high power modelocked lasers on chip.

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