Title

Review of “Laser soliton microcombs heterogeneously integrated on silicon” at a Introductory Graduate Laser Course Level

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Review of "Laser soliton microcombs heterogeneously integrated on silicon" at a Introductory Graduate Laser Course Level

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Abstract

In this paper review, I will explain the fundamentals of a "laser soliton microcomb heterogeneously integrated on silicon", presented by Xiang et. al of the Bowers Lab at UCSB [1]. I will try to relate concepts taught in class, which will be **bolded**, while presenting new material at a level that can be understood by someone who only has understanding of basic optics as well as the theory, components, and operation of a traditional Fabry-Perot cavity laser.

In this paper Xiang et. al present the design, the underlying photonics principles used, their fabrication process and considerations, and finally performance measurements and verification of the final device.

Prior Art

While both semiconductor DFB lasers as well as laser soliton microcombs on a chip have been demonstrated, the integration of both onto a single heterogeneous Si, Si_3N_4, and InP wafer chip has not been demonstrated before [1].

Such a device is useful for fiber optic applications, where the generation of light is needed to send signals over fiber. A laser that is able to generate solitons is ideal because the minimizes dispersion as the optical signal propagates through the fiber. This is of special importance in coherent optical communications, which extend beyond simple amplitude modulation and rely on phase and polarization information as well [18].

What is Integrated Photonics?

A waveguide (Figure 1) is a device which guides the propagation of light along a certain direction. It can be made of metal or dielectric, and is often in the shape of a cylinder or rectangular prism. For the optical regime, dielectrics are most commonly used due to the high losses in metal at THz frequency. A waveguide relies on reflection against the walls to confine the optical power – in the case of dielectric, total internal reflection. This means that the inside of the waveguide will have a higher refractive index n than the outside. If a waveguide is narrow enough, it will only allow the most fundamental mode to propagate, akin to the root in a series of harmonics. This fundamental mode has a field strength distribution very similar to that of a **Gaussian beam** (Figure fc) – but note that the field does not expand outward, instead maintaining its size and shape as it propagates.

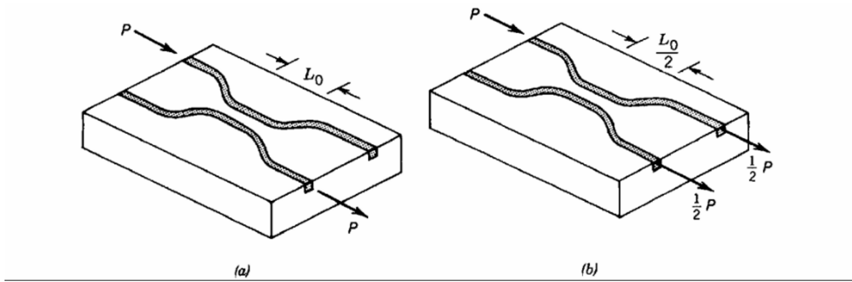
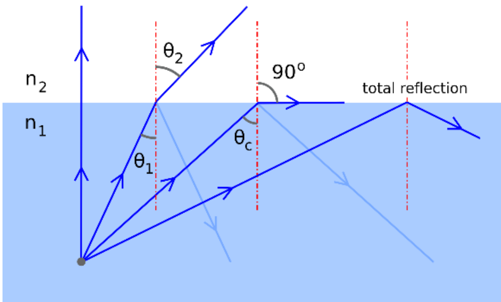


Figure 1 Optical couplers: (*a*) switching of power from one waveguide to another; (*b*) a 3-dB coupler.



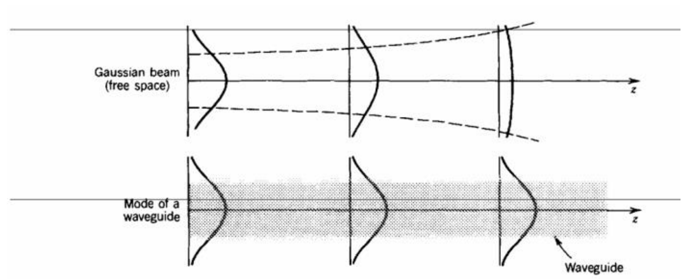


Figure 7.2-7 Comparison between a Gaussian beam in free space and a waveguide mode.

Fig. 1: Top: Diagram of waveguide structure [2]. Bottom left: Illustration of concept of total internal reflection [3]. Bottom right: propagation of Gaussian beam in free space vs. waveguide mode. Note that waveguide mode maintains shape [3].

Often, when *integrated* onto a silicon wafer, the interior material will be made of Si or Si_3N_4 (silicon nitride), and the outside will be oxide or some lower index dielectric like SiO_2. Additionally, waveguides can be integrated with optical sources, modulators, and detectors, all on a single chip, enabling miniaturization of entire optical systems. A common usage of this is in fiber optic communications (optical transceivers), as well as emerging fields of optical and quantum computation as well as sensing.

What is dispersion and solitons?

A key metric of propagating light is its *dispersion*, which describes how well an optical pulse stays together as it propagates, rather than spreading out in time. Most media have "normal" dispersion, meaning that refractive index n increases with longer optical wavelength – meaning that in an propagating optical pulse, the larger wavelengths will begin to lag behind while shorter wavelengths pull ahead, resulting in a broadening or *dispersion* of the pulse.

A *soliton* is a pulse which does not disperse as it propagates. In the temporal case (which is most often what the term refers to), this is achieved by a combination of anomalous (group velocity) dispersion (GVD) as well as the optical Kerr effect. This will be explained further below, but the key fact is that the Kerr effect results in a dispersion in the opposite direction – if balanced correctly, the leads to light propagating with no dispersion, as a *soliton*.

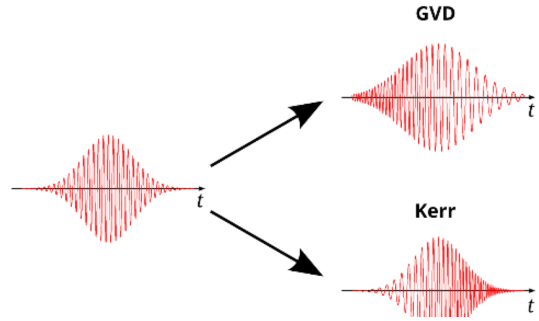


Figure 2: Anomalous GVD Dispersion and Kerr effect dispersion [5]

Solitons are very useful in long-distance optical propagation, such as optical fiber communications where light is modulated into discrete pulses to communicate information.

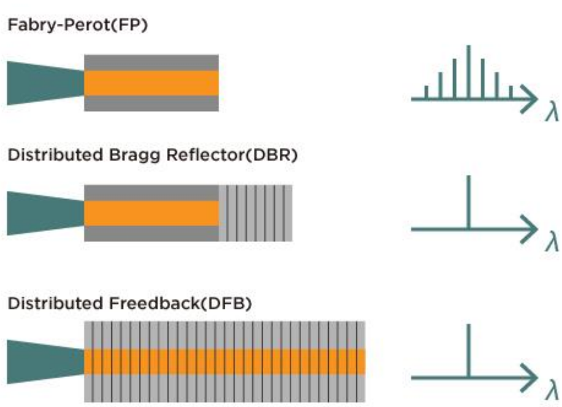
What is a Distributed Feedback Laser (DFB)?

We are familiar with the concept of a **Fabry-Perot** resonator, where the reflections from the cavity walls result in constructive and destructive interference, allowing only certain wavelengths of light to pass.

A Bragg reflector utilizes a similar principle, except that multiple FP-cavities are placed in series, resulting in *distributed feedback*.

In a distributed feedback laser, the entire **gain media** is located in or coupled to a Bragg reflector, resulting in a very consistent and stable **center optical frequency** when lasing. When embedded in an optical fiber, it can result in very narrow **linewidth** [8, 9].

The authors of this paper utilized this design for the laser source on their chip.



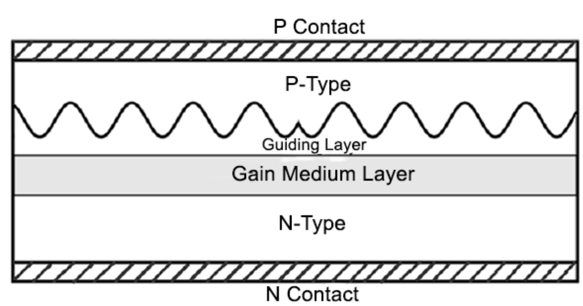


Fig. 3. Left: DBF laser gain media. Right: practical implementation of semiconductor DFB [6, 7]

What is Nonlinear Optics / Kerr Effect

The Kerr effect in a material is the increase in index of refraction of a material proportional to the *square* of an applied electric field. This makes this effect a *nonlinear* optical effect, though it is quite weak at everyday intensities.

However, at very strong optical intensities, achievable with a laser (~1GW/cm^{-2}), the electric field from the propagating light is able to self-induce an AC or Optical Kerr effect in the material of propagation. This can result in a behavior known as *self focusing*, where the medium acts as a graded refractive index (**GRIN**) lens. This can prevent or reduce spatial dispersion, or in extreme cases, focus light so much that the material is damaged.

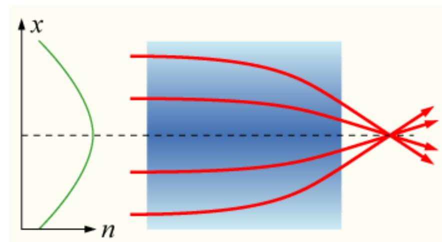


Figure 4: Self-focusing effect [7]

Additionally, the AC Kerr effect causes *self-phase modulation,* which leads to the temporal dispersion effect depicted above in Figure 2. This, combined with anomalous dispersion, leads to optical *solitons* with zero *dispersion*. [10], [11]

Four Wave Mixing/ Kerr Frequency Comb

Four wave mixing (FWM) is another effect within nonlinear optics.

When a signal light source of a certain wavelength and pump of a different wavelength are introduced to each other, a third "idler" wavelength is generated. Figure 4 depicts a specific case of this known as "degenerate four wave mixing" with only two inputs rather than three.

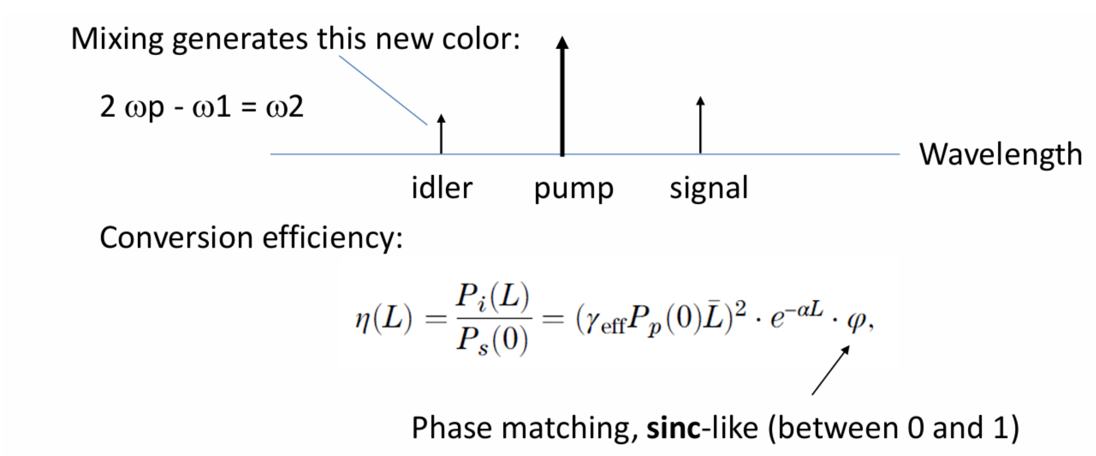


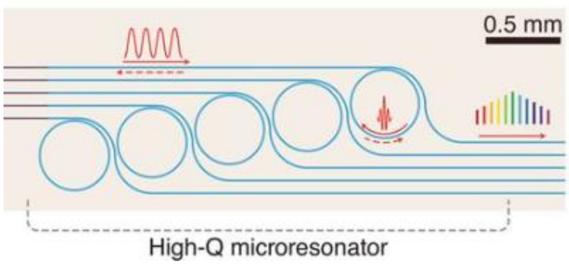
Figure 5: Four wave mixing [14]

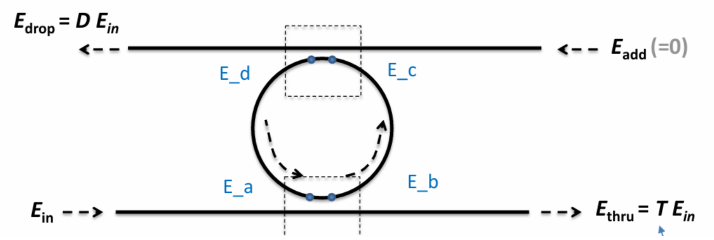
A *Kerr frequency comb* relies on the optical Kerr effect described previously to facilitate FWM, even only one wavelength input [13].

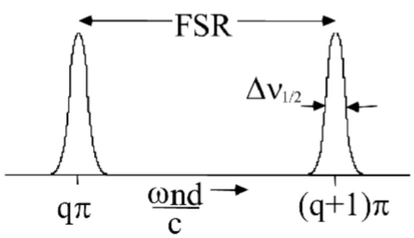
What is microresonator?

A microresonator or ring resonator is an photonic waveguide structure which is aptly shaped like a ring. It acts similarly to a **Fabry-Perot** resonator, where one trip around the ring is equivalent to one **unit cell**. The circumference of the ring, analogous to **round-trip** distance, determines the **FSR** of the resonator. Similarly, the concepts of **Q-factor** as well as **finesse** also apply. However, it may be more helpful to think of the Q-factor with the definition of 2π times the ratio of the stored energy to the energy dissipated per oscillation cycle. In this context, a high-Q ring resonator is achieved by ensuring the ring has low losses, as well as optimizing the transmission and coupling conditions between the ring and waveguide [12].

Microresonators are commonly used to couple light between waveguides as well as act as a filter that favors specific resonant wavelengths.







$$F = \frac{\text{Free Spectral Range}}{\text{Full-width-at-half-maximum}} = \frac{(c/2nd)}{\Delta\upsilon_{1/2}}$$

$$FSR = \frac{c}{2nd} \qquad Q = \frac{\upsilon_0}{\Delta\upsilon_{1/2}} = 2\pi\,\frac{\text{(energy stored in cycle)}}{\text{(energy dissipated in cycle)}}$$

Figure 6. Top left – image of a series of parallel microring resonators [1]. Top right: Each resonator can be visualized as 4-port system, where part of the input power couples to the opposite side [14]. Bottom: important relevant equations for resonant cavities still apply to ring resonators [4].

Overall Design

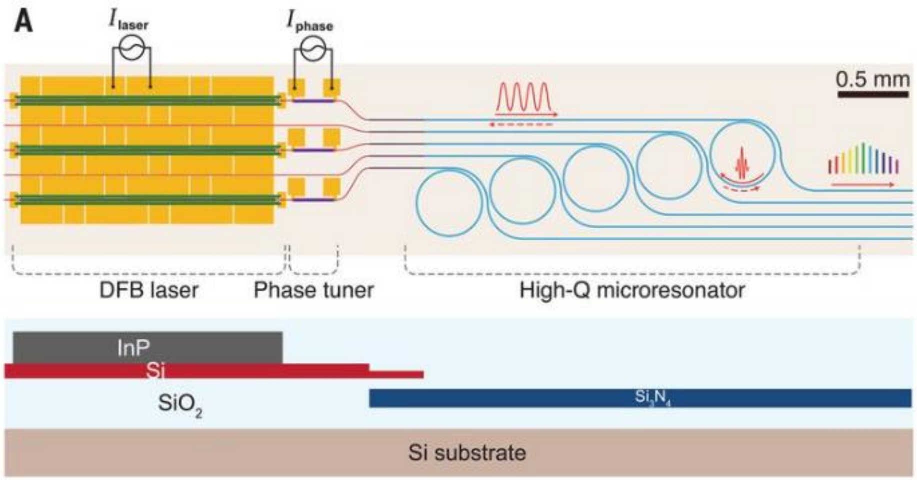


Fig. 7: (**A**) Schematic of laser soliton microcomb devices consisting of DFB lasers, phase tuners, and high-*Q* microresonators on a common substrate. A continuous-wave signal (solid red line) emitted from the laser is coupled into the microresonator and partially backscattered. The backscattered signal (dashed red line) to the laser triggers self-injection locking that assists soliton formation inside the microresonator. The locking is optimized by controlling the laser current Iaser and phase tuner current Iphase. [1]

Illustrated in figure 7 is the design of the chip. DFB lasers feed into a parallel collection of microring resonators, which then lead to the laser output. The lasers are fabricated using InP, which are then bonded to a Si substrate. The light is then coupled into a Si_3N_4 waveguide and microrings grown on the same Si substrate.

In this case, the paper authors use the microresonator as a tool to increase the intensity of the light, increasing Kerr effect inside the ring and enhancing soliton formation. In a way it acts as an optical version of an inductor.

Additionally, the ring resonators provide **optical feedback** to enhance a phenomenon known as *injection locking*, where the backpropagated light re-enters the gain media and further stabilizes the laser, reducing intensity and phase noise. This reduces the **linewidth** of the laser, further reducing dispersion and enhancing soliton behavior.

Analysis

The **linewidth**, **FSR**, and **resonances** of the device are measured by the authors. The microring resonators support soliton "crystal states" of 2x, 3x, and 4x FSR. One can read more about soliton crystals at [16, 17]. One of the big advantages of microrings is that their small size enables relatively large FSR (GHz range). Notice that the central wavelength has the strongest output and others decrease away from centerline. In a practical system the powers would need to be balanced in some way, if Wavelength Division Multiplexing (WDM) is to be used, where multiple light wavelengths are sent through a single fiber.

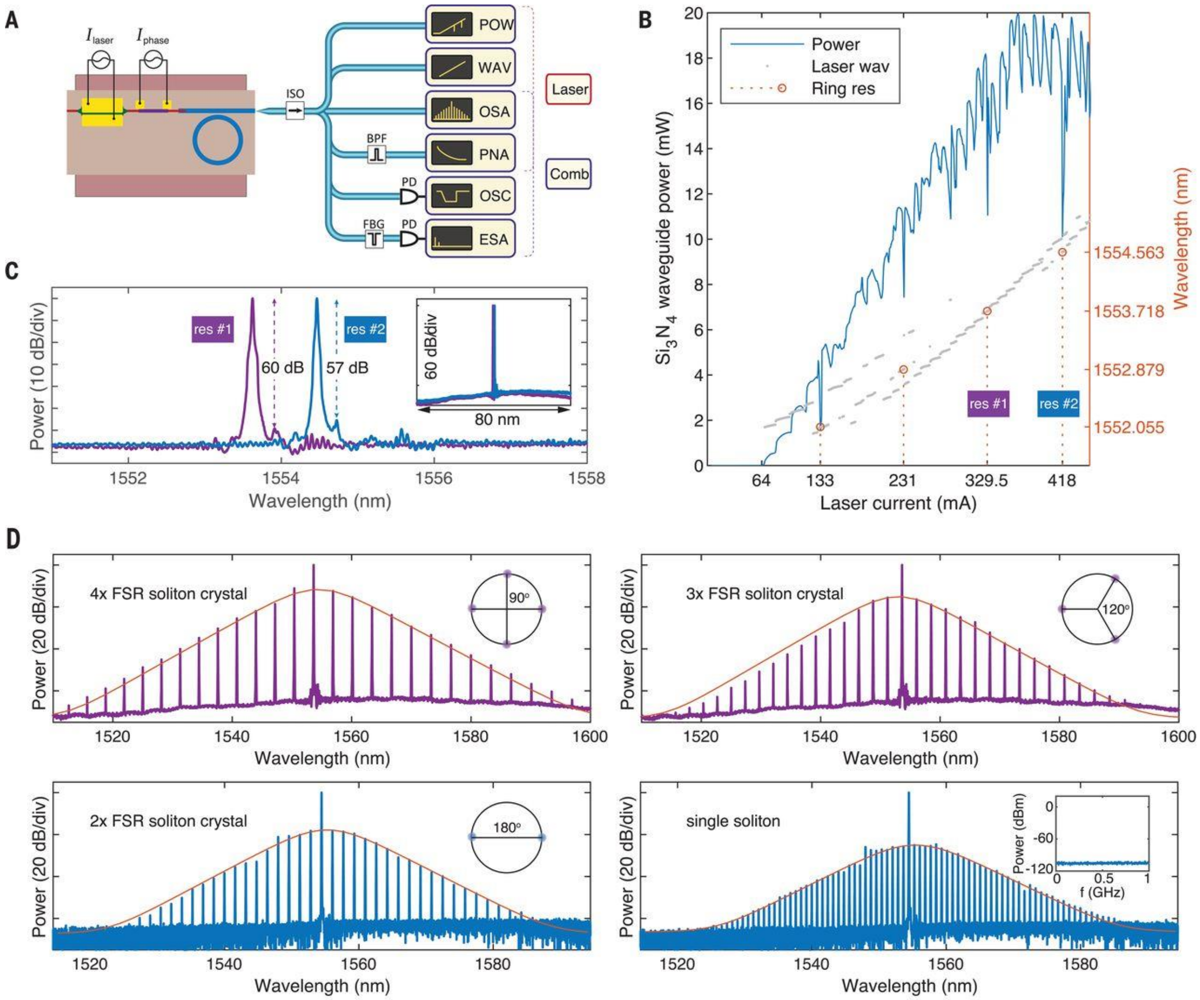


Fig. 8 Device characterization and experimental generation of soliton spectra.

(**A**) Experimental setup for laser and soliton characterization. Ilaser and Iphase are the current sources to drive the laser and the phase tuner. POW, power meter; WAV, wavelength meter; OSA, optical spectrum analyzer; PNA, phase noise analyzer; OSC, oscilloscope; ESA, electrical spectrum analyzer; ISO, isolator; BPF, band-pass filter; FBG, fiber Bragg grating; PD, photodetector. (**B**) Light-current sweep measurement with stepped laser current and fixed phase tuner current. Gray color shows the corresponding laser center wavelength as a function of the laser current. Red circles indicate the laser wavelength coinciding with microresonator resonances. Soliton microcombs are generated with laser currents and wavelengths at resonance #1 and resonance #2. (**C**) Single-mode DFB laser spectra at the wavelengths of resonance #1 and resonance #2. (**D**) Optical spectra of soliton states. Inset shows the relative position of multi-solitons circulating inside the microring resonator for four-, three-, and two-FSR soliton crystal states and low-frequency radio-frequency spectrum of the single-soliton state.

Excellent performance is demonstrated, with the “self-injection–locked single soliton state” able to reduce the **linewidth** of the DFB laser from 60kHz to 25Hz, which is astonishingly low. Noise reduction of at least 10dB is also observed at 10kHz and above, compared to the free running laser (Figure 9a).

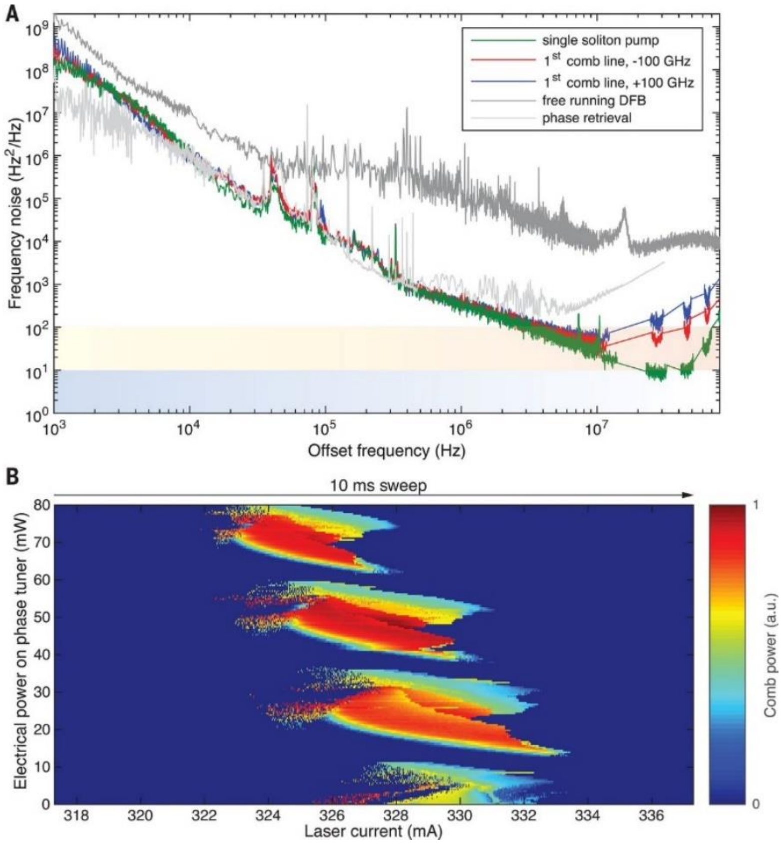


Fig. 9

(A) Frequency noise spectra of the self-injection–locked pump line (green), comb lines with GHz frequency offset to the pump (blue and red) in the single-soliton state, free-running single-mode DFB laser output without self-injection locking (dark gray), and comb line around 1550 nm for the two-FSR soliton crystal state using optical phase retrieval method (25). (B) Comb power evolution with sweeping laser current (10 ms sweep) under varying electrical power on the phase tuner. [1] One can see that lasing action is highly dependent on phase of optical feedback, necessitating the electrical tuners in the design.

I will not discuss it here, but the authors also mention various techniques they use to achieve a high fabrication yield, which is limited by "SOI bonding and InP bonding yields." They also achieve a less than 1dB loss for the InP/Si-to-Si rib waveguide transition and simulate the Si-to-Si_3N_4 mode conversion efficiency to be above 90%. These factors are key considerations in producing a power efficient laser, which is of chief concern in the telecom industry where power differences add up quickly.

Criticisms/Future Directions

The authors did not long-term stability of the laser output, both in intensity and wavelength. These may be important considerations if eventually this is intended to be used in a telecom application. Additionally, the solitons are formed, but the exact coherence is not measured. The paper mentions they are confirmed from observation of "low-intensity noise from the comb lines beating" and that "the soliton states can be stable for hours in standard laboratory environments without any external feedback control," but they do not quantify specific figures. Finally, the current minimum pumping power for the microresonators is 16mW and power outcoupled to fiber is 8mW, meaning the total power draw is higher than 16mW (specific power draw not mentioned in paper). This number is on the higher side for near range telecom applications, and lower side for long range telecom [15]. It should be investigated if a lower minimum power can be achieved, potentially through a more efficient design or better mode confinement, as well as how amplification of the output can be achieved without negatively affecting noise characteristics. Overall however, creating solitons through nonlinear Kerr effect with only 16mW of power is a great and notable achievement, especially on a single integrate chip.

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