Widely Tunable and Narrow Linewidth Laser Source based on Normal-Dispersion Frequency Combs and Optical Injection Locking

Citation for the original published paper (version of record):
Skehan, C., Helgason, Ò., Schröder, J. et al (2022). Widely Tunable and Narrow Linewidth Laser Source based on Normal-Dispersion Frequency Combs and Optical Injection Locking. Optics InfoBase Conference Papers

Research Article | Vol. 30, No. 13 / 20 Jun 2022 / *Optics Express* 22388

Optics EXPRESS

Widely tunable narrow linewidth laser source based on photonic molecule microcombs and optical injection locking

J. CONNOR SKEHAN, ÓSKAR B. HELGASON, JOCHEN SCHRÖDER, VICTOR TORRES-COMPANY, AND PETER A. ANDREKSON*

Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE - 412 96 Gothenburg, Sweden
*Peter.Andrekson@Chalmers.SE

Abstract: We demonstrate a method to generate a widely and arbitrarily tunable laser source with very narrow linewidth. By seeding a coupled-cavity microcomb with a highly coherent single-frequency laser and using injection locking of a Fabry-Perot laser to select a single output comb tone, a high power, high side mode suppression ratio output wave is obtained. The system is demonstrated across 1530 -1585 nm with a linewidth below 8 kHz, having 5 dBm output power and sidemode suppression of at least 60 dB. Prospects of extending the performance are also discussed.

1. Introduction

Ongoing research continues to produce new single frequency laser sources which have low noise and are highly tunable, such that they may be used for communications, metrology, resonant excitation of various physical systems, and more. Currently, there are a variety of approaches to produce such lasers [1], including DFB lasers [2], DBR lasers [3], and external cavity lasers [4]. Key parameters of interest include width of the tunable range, and the phase and intensity noise of the final output, as well as the OSNR.

Here, we propose and implement a scheme based on a modification of our design in [5], whose schematics are given in detail in Fig. 1(a). A DFB slave laser provides pre-amplification of a highly coherent seed laser which is tunable over 115 GHz via injection locking, which is then used to pump an on-chip coupled-cavity microcomb (also refered to as a photonic molecule) to produce an optical frequency comb with a free spectral range (FSR) of ~100 GHz [6]. A set of filters (0.1 nm flat-top bandwidth with 3 dB injection loss), a semiconductor based optical amplifier (SOA with 15 dB gain), and a custom Fabry-Perot (FP) slave laser are then used for post-comb injection locking and cleanup of the selected tone in order to produce the final single frequency output. Importantly, two heaters are placed on the primary and auxiliary ring of the coupled cavity system such that the induced modal crossing and thus center frequency of the comb can be tuned over more than 1.75 FSR - ensuring that any arbitrary frequency generation is possible.

From a 'black box' perspective, the approach effectively extends the tunable range of the seed laser, albeit at the cost of some excess phase and intensity noise which increases as a function of the frequency difference between the locked mode and the frequency of the seed laser. Moreover, this a scheme is capable of locking to multiple tones simultaneously, enabling the production of simultaneously coherent tones at different frequencies, which is not possible with conventional techniques. There is some very recent work which has explored this opportunity [7], but which relies on anomalous dispersion combs with low conversion efficiency and which lack a flat top

#457937 https://doi.org/10.1364/OE.457937
Journal © 2022 Received 11 Mar 2022; revised 22 Apr 2022; accepted 30 Apr 2022; published 6 Jun 2022

Optics EXPRESS

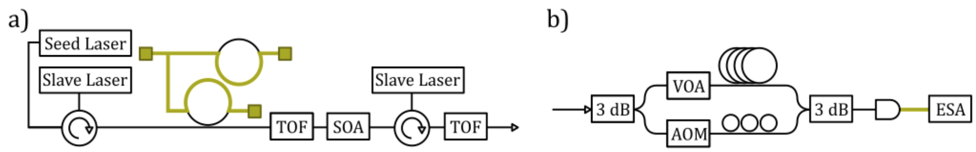

Fig. 1. a) The principle of operation, using pre-injection locking DFB laser, comb generation in a photonic molecule, a set of tunable optical filters (TOF), a semiconductor optical amplfier (SOA), and a post-injection locking Fabry-Perot laser b) Phase noise measurement using a variable optical attenuator (VOA), acousto-optic modulator (AOM), and an electric spectrum analyser (ESA). Here the yellow lines represent electronic signals, while the black lines represent optical paths.

optical spectrum, both of which are highly desirable features for the production of comb-based single frequency sources. Moreover, due to the lack in overlap between the comb spacing, comb center frequency tunability, and seed laser tunability, this previous work was incapable of truly arbitrary frequency generation, in contrast to the work presented here.

Our previous work [5] in the field relied on an electro-optic (EO) comb and an array of DFB slave lasers, both of which are bulky and energy inefficient. In this work however, instead of using an EO comb, we generate a microresonator frequency comb (microcomb) using a normal-dispersion photonic molecule configuration [6]. In contrast to traditional dissipative Kerr solitons made in anomalous dispersion cavities [8,9], such photonic-molecule microcombs can offer bandwidths far beyond the range of EO combs, while maintaining ample line power for injection locking and allowing for arbitrary central frequency of the comb, and high conversion efficiency [10]. Moreover, instead of an array of DFB slave lasers, we use a single Fabry-Perot slave laser and tunable optical filter in series to remove spurious tones, a design change which improves scalability and cost.

To produce the final output tone, we first begin with a fiber laser which is tunable over less than 1 nm and which has < 100 Hz linewidth, but after generation of the frequency comb and subsequent injection locking of individual tones, we achieve approximately 55 nm of arbitrary tunability across the full C-band and beyond (1530 nm to 1585 nm), >60 dB of SMSR, and > 5 dBm of power across the full range. The intensity and phase noise vary as a function of comb mode index, m, and are measured for every other tone. In all cases, the integrated linewidth of the source is less than 8 kHz [11], and the RIN at 1 GHz is less than −140 dBc/Hz.

Several other approaches to the same problem of simultaneously maintaining high tunability and low noise have also been implemented using integrated photonic waveguides and resonators, some of which have better phase noise performance. One common approach uses self-injection locking of a nonlinear ring resonator [12–15] via back scattered modes or wavelength selected modes, although tunability remains low. Other methods also rely on counter propagating feedback onto the seed laser, and can best be described as a chip-extended external cavity laser [16,17]. Our case is particular, however, in that it fully bypasses the need for optical feedback onto the seed laser (i.e. the injection locking mechanism is wholly separate from the source such that no self-injection locking is present), which is crucial for a variety of applications such the production of mutually coherent tones at different frequencies [7] and opens up the opportunity for straightforward backward pumped laser cooling of the photonic molecule, which comes in many forms [18,19].

There has also been some interest recently in the external injection locking of comb tones to study their mutual coherence such as in [7], which supports the claim that any two generated tones will remain mutually coherent even after external injection locking. Moreover, optical injection locking of comb tones has also seen use in the field of communications [20], where amplification of comb lines via OIL offers marked improvement over amplification via EDFA.

Optics EXPRESS

Similar results have been seen when injection locking mode locked lasers with ultra-dense mode spacing [21]. That being said, these approaches suffer from low optical and electrical efficiency, the wasting of comb lines due to a mismatch in the optical tuning range of the slave laser and the FSR of the comb, major inconsistencies in injection ratio due to the fact that the combs used do not have a flat spectral profile, and the inability to produce optical tones at an arbitrary frequency. Moreover, these approaches lack the ability to cover the full optical C-band.

2. Experimental details

In general, a frequency comb can be thought of as a series of mutually coherent and equally spaced non-zero amplitude tones in the frequency domain. In our case, we generated a photonic molecule microcomb in a cavity which is linearly coupled to a slightly larger auxiliary cavity, both having normal dispersion. This results in an avoided mode-crossing, whose location can be arbitrarily controlled via individual heaters on each cavity [22]. By configuring the mode-crossing in a similar manner as in [6], we can deterministically initiate a dissipative soliton in the main cavity, corresponding to a comb output with a 100 GHz FSR. A typical output and corresponding set of simulation data is shown in Fig. 2(a), for which a power conversion ratio of $\sim 33\%$ is obtained.

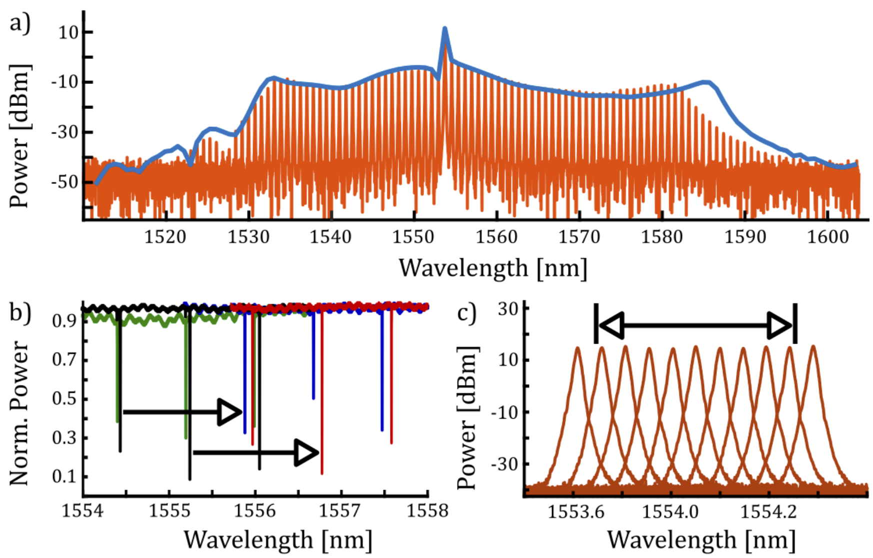

Fig. 2. a) Measured (in orange) and simulated (in blue) comb spectra b) Tunability of the resonator modes with 0 and 15 V applied to the primary ring (green to blue) and auxiliary ring (black to red) c) Tunable range of the low noise fiber laser (in orange) as compared to the comb FSR (in black).

To demonstrate that the modal crossing can be induced anywhere, we show the extrema of individual modes from the cold cavity's transmission, after applying 0V and 15V (Fig. 2(b)) on the heaters of both the primary and auxiliary cavities. Indeed, well over 1.75 FSR of thermal shift is observed. Moreover, we show in Fig. 2(c) the output spectra and tunability of the fiber laser used to produce the frequency comb, with the FSR of the comb marked with a black arrow. Because the seed laser is tunable over a range larger than the FSR, and because the modal crossing can be induced over a span grater than one FSR, an overlap between the two can be produced at any frequency, and thus comb generation at an arbitrary central frequency is possible.

Optics EXPRESS

One of the same DFB slave laser from Gooch and Hoosego used in [5] was used for amplification via injection locking of the seed laser before generation of the soliton. It has already been shown that the injected optical field can force the cavity to oscillate in a manner which follows the frequency and phase properties of the seed laser with little to no penalty in RIN or phase noise. For this specific DFB slave laser, an input power of ~ -30 dBm was required for stable operation, and the output power was ~ 20 dBm.

The FP slave laser's injection locking characteristics are presented in Fig. 3(a). Here, we measure the side mode suppression ratio of the unfiltered, but injection locked output from the FP laser, as a function of injection ratio - the ratio of input power to total output power of the slave laser. In general, for best performance, and to guarantee >5 dBm of total output power from the system after final filtration, an injection ratio of approximately −25 dB was required, corresponding to approximately −15 dBm of input power to the Fabry-Perot laser's cavity, which necessitated the use of an SOA before injection locking.

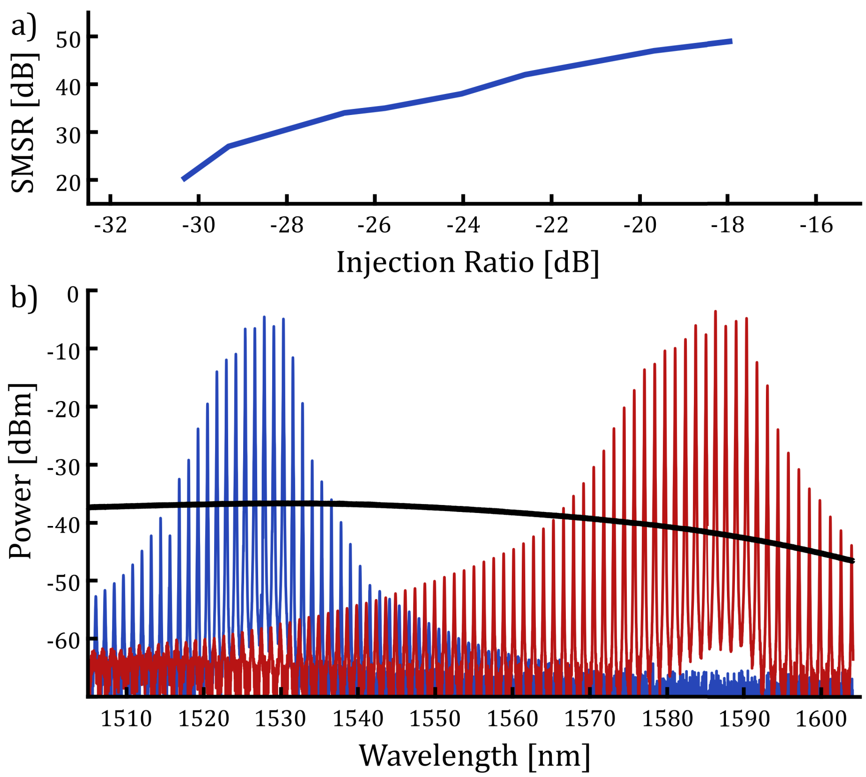

Fig. 3. a) Side mode suppression ratio of the Fabry-Perot laser before final filtration b) Spectra of the unlocked slave laser at its lowest (in blue) and highest (in red) possible wavelength, along with the amplified spontaneous emission spectrum of the SOA in black.

In Fig. 3(b), the ASE spectrum of the SOA, which has a gain of approximately 15 dB at the edge of the product's given specification range (C+L band), and which is higher between (up to 23 dB), is given. This corresponds to a required power for a useful tone in the comb of approximately −30 dBm at the edges of operation (given that −15 dBm of input power is required for stable injection locking of the FP slave laser). The extremes of operation for the FP laser itself are also given, using temperature tuning only, which demonstrate that the limiting factor for the operable tuning range is the frequency comb, although only by ~ 10 nm, and that temperature tuning alone is sufficient to cover the full available bandwidth.

Optics EXPRESS

3. Results and discussion

Using the aforementioned methods, we produce final output tones which have their intensity and phase noise measured. Looking back at the typical comb spectra from Fig. 2(a) and using −30 dBm as our cutoff for useful operation, we are therefore able to cover the full C-band and beyond, from approximately 1530 nm to 1585 nm. Indeed, in Fig. 4(a), we show a variety of output tones with power > 5 dBm across the wavelength range, and beneath in Fig. 4(b) we show corresponding RIN measurements. For consistency, all measurements in the paper are derived from the same comb spectrum as seen in Fig. 2(a)].

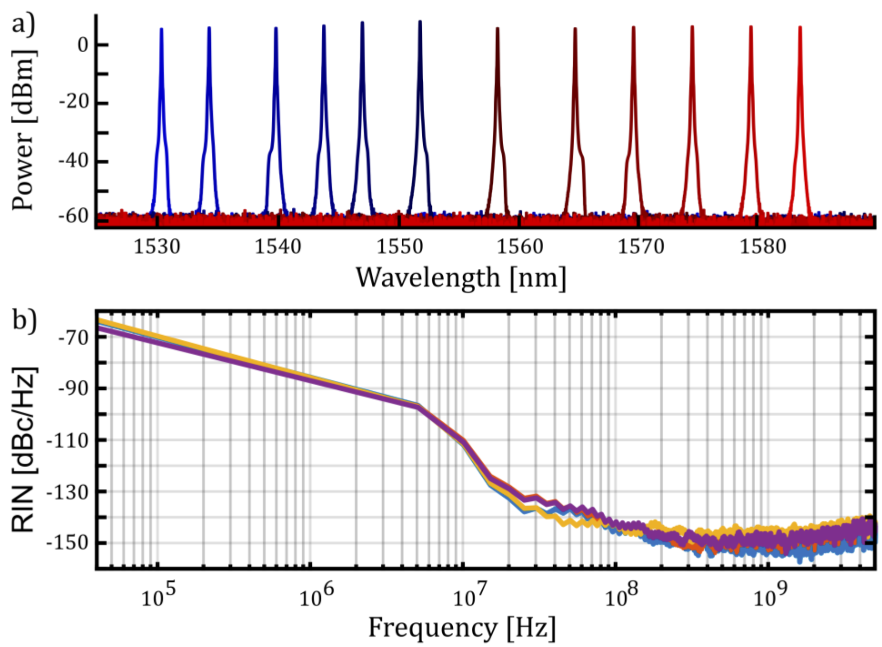

Fig. 4. a) Various tones across the C-band (black arrow) and beyond, after final injection locking and mode clean up, as measured on an OSA with 0.1 nm resolution. b) Relative Intensity noise of the seed laser (in blue), m = 0 tone (in orange) and the extreme tones at m = −30 (in purple) and m = +36 (in yellow).

We show the RIN power spectral density for the seed laser before pre-injection locking, as well as the m =0, m = −30, and m = +36 final output tones, and show that the RIN penalty is less than 10 dB.

After the final coherent tone is produced, its phase noise is measured using the well understood delayed self-heterodyne method, using the setup described above placed in a bespoke, sound isolating box. In this case, an AOM with driving frequency 27.12 MHz and a delay line with length 25 km are used. This corresponds to approximately 125 μs (the inverse of which is ~ 8 kHz) of optical delay, which sets the lower limit on accurate integrated linewidth measurements.

There is a significantly larger variation in the phase noise between modes than was the case for RIN, as would be expected based on previous phase noise measurements of comb tones [19]. In Fig. 5(a), we show the unlocked seed laser in blue, and every other comb mode after final injection locking and filtration in shades of red, up to the m= −30 and m = +36 modes. In the inset, we show the integrated phase noise from 8 kHz (corresponding to the delay line length in measurement), up to 125 MHz (the bandwidth of the photoreceiver).

Optics EXPRESS

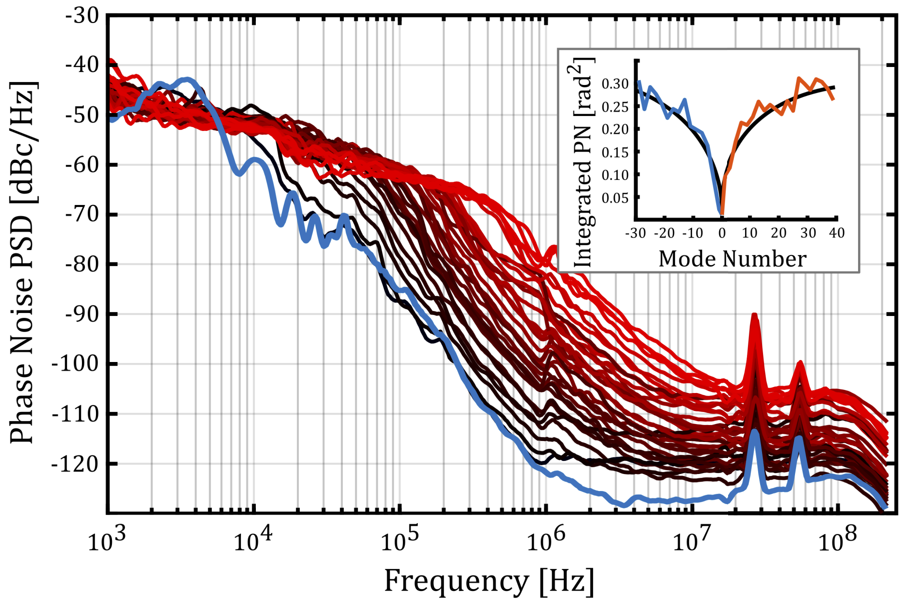

Fig. 5. a) The phase noise of the fiber laser (in blue) as compared with every other mode spanning from m = −30 to m = +36. Low absolute mode numbers are darker, while higher absolute mode numbers are brighter. Inset) The integrated phase noise from 8 kHz to 125 MHz, for each mode.

If we assume that the phase noise of the seed laser is approximately equal to the 0th order tone, we can write an expression for the single sideband phase noise PSD as [23]

$$L_m(f) = L_{cw}(f) + m^2 \cdot L_{rep}(f), \tag{1}$$

where L_{rep} corresponds to the noise spectral density of the comb's repetition rate. While various factors drive the repetition rate noise, it has been shown that for microresonators of approximately 100 GHz FSR, this term is dominated by thermorefractive noise [24], although several other noise sources are present as well [25]. As expected, the integrated phase noise measurements over the full measured bandwidth as seen in the inset of Fig. 5 matches the quadratic model well.

Using the definition of integrated linewidth [11],

$$\int_{\delta\nu_{int}}^{\infty} S_\phi(f)df = \frac{1}{\pi}, \tag{2}$$

and based on the measurements seen in the inset of Fig. 5, for all final output frequencies across the source's full bandwidth, the integrated linewidth is less than 8 kHz, given that the integrated phase noise remains below $\frac{1}{\pi}$.

4. Conclusion and future outlook

In conclusion, we have successfully demonstrated a laser source which is tunable over 55 nm (including the full C-band), and which has >60 dB SMSR, >5 dBm of output power, and modest penalty in RIN over the full tunable bandwidth. Moreover, phase noise measurements demonstrate that for all achievable frequencies, the integrated linewidth is lower than 8 kHz. The system effectively uses the production of Kerr frequency combs and subsequent injection locking of comb tones to nonlinearly extend the tunable range of a low noise seed laser.

Optics EXPRESS

Our previous result using a DFB laser laser array and EO-comb provided 10 nm of optical tunable bandwidth, > 55 dB of SMSR, ∼ 20 dBm of ouput power, and had < 400 Hz linewidth across it's full bandwidth, but came with significant downsides in terms of control electronics, efficiency, and footprint.

Compared to our previous result using an EO-comb, this system is 5.5x more tunable (and importantly covers more than the full C-band), has a higher SMSR, and is more efficient and compact, but comes at the cost of output power and phase noise. Furthermore, it does not require an EDFA. Moreover, the system is scalable, and many of the limitations can be addressed, which indicates that even higher performance systems are possible based on the same approach.

For instance, low noise fiber laser sources can be twice as tunable as the one used here, which allows for doubling of the tuning range if we assume the same number of comb tones and double the FSR. Assuming an equal number of comb lines, coverage of > 100 nm of tunable range is possible, assuming a sufficiently broadband SOA and slave laser setup. Alternatively, compression and/or amplification may be used along a highly nonlinear medium such as highly nonlinear fiber or silicon waveguides may be used to produce a sufficiently broadband comb.

Moreover, the current phase and linewidth limits for the system stem from repetition rate noise due to (in this parameter space) thermorefractive noise of the integrated photonic platform - a well understood problem with several known solutions. In particular, laser cooling of the resonator may be used to reduce thermorefractive noise, which quickly dominates as m increases. Doing so, however, requires backwards propagating light, which might prove this solution difficult to implement in self-injection locked system. Using this approach however, one could forward pump with an ultra low noise laser, while simultaneously laser-cooling the cavity with a backwards pumped and blue detuned optical frequency [18,19].

The fact that this approach is feedback free on the seed laser is useful for a variety of other applications as well. Chip powered external cavity lasers are only able to produce one tone at a time, while a device such as this could be easily configured to two or more mutually coherent tones from the same comb, as studied in [7].

All together, we believe this represents a promising application for frequency combs, as well as a potentially viable method to produce arbitrary frequency and turnkey laser solutions. The principle of arbitrary frequency generation is demonstrated here, while turnkey operation has been demonstrated elsewhere [26].

Funding. Vetenskapsrådet (VR-2015-00535); Knut och Alice Wallenbergs Stiftelse.

Acknowledgements. Funding was provided by the following : Knut och Alice Wallenbergs Stiftelse, Vetenskapsrådet (VR-2015-00535 & 2020-00453), and ERC (GA 771410).

The authors would also like to thank Fuchuan Lei for our fruitful conversations, and extensive reading suggestions.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. S. Fu, W. Shi, Y. Feng, L. Zhang, Z. Yang, S. Xu, X. Zhu, R. A. Norwood, and N. Peyghambarian, "Review of recent progress on single-frequency fiber lasers," J. Opt. Soc. Am. B **34**(3), A49–A62 (2017).
2. R. Tkach and A. Chraplyvy, "Phase noise and linewidth in an InGaAsP DFB laser," J. Lightwave Technol. **4**(11), 1711–1716 (1986).
3. Y. Kotaki, M. Matsuda, H. Ishikawa, and H. Imai, "Tunable DBR laser with wide tuning range," Electron. Lett. **24**(8), 503–505 (1988).
4. T. Komljenovic, S. Srinivasan, E. Norberg, M. Davenport, G. Fish, and J. E. Bowers, "Widely tunable narrow-linewidth monolithically integrated external-cavity semiconductor lasers," IEEE J. Sel. Top. Quantum Electron. **21**(6), 214–222 (2015).
5. J. C. Skehan, C. Naveau, J. Schroder, and P. Andrekson, "Widely tunable, low linewidth, and high power laser source using an electro-optic comb and injection-locked slave laser array," Opt. Express **29**(11), 17077–17086 (2021).
6. Ó. B. Helgason, F. R. Arteaga-Sierra, Z. Ye, K. Twayana, P. A. Andrekson, M. Karlsson, J. Schröder, and V. Torres-Company, "Dissipative solitons in photonic molecules," Nat. Photonics **15**(4), 305–310 (2021).

Optics EXPRESS

7. N. Kuse and K. Minoshima, "Amplification and phase noise transfer of a Kerr microresonator soliton comb for low phase noise Thz generation with a high signal-to-noise ratio," Opt. Express **30**(1), 318–325 (2022).
8. T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, "Temporal solitons in optical microresonators," Nat. Photonics **8**(2), 145–152 (2014).
9. T. J. Kippenberg, A. L. Gaeta, M. Lipson, and M. L. Gorodetsky, "Dissipative Kerr solitons in optical microresonators," Science **361**(6402), eaan8083 (2018).
10. X. Xue, P.-H. Wang, Y. Xuan, M. Qi, and A. M. Weiner, "Microresonator Kerr frequency combs with high conversion efficiency," Laser Photonics Rev. **11**(1), 1600276 (2017).
11. M. A. Tran, D. Huang, and J. E. Bowers, "Tutorial on narrow linewidth tunable semiconductor lasers using Si/III-V heterogeneous integration," APL Photonics **4**(11), 111101 (2019).
12. B. Stern, X. Ji, A. Dutt, and M. Lipson, "Compact narrow-linewidth integrated laser based on a low-loss silicon nitride ring resonator," Opt. Lett. **42**(21), 4541–4544 (2017).
13. N. Pavlov, S. Koptyaev, G. Lihachev, A. Voloshin, A. Gorodnitskiy, M. Ryabko, S. Polonsky, and M. Gorodetsky, "Narrow-linewidth lasing and soliton Kerr microcombs with ordinary laser diodes," Nat. Photonics **12**(11), 694–698 (2018).
14. C. Xiang, J. Guo, W. Jin, L. Wu, J. Peters, W. Xie, L. Chang, B. Shen, H. Wang, Q.-F. Yang, D. Kinghorn, M. Paniccia, K. J. Vahala, P. A. Morton, and J. E. Bowers, "High-performance lasers for fully integrated silicon nitride photonics," Nat. Commun. **12**(1), 6650 (2021).
15. G. Lihachev, J. Riemensberger, W. Weng, J. Liu, H. Tian, A. Siddharth, V. Snigirev, R. N. Wang, J. He, S. A. Bhave, and T. J. Kippenberg, "Ultralow-noise frequency-agile photonic integrated lasers," arXiv preprint arXiv:2104.02990 (2021).
16. Y. Fan, A. van Rees, P. J. Van der Slot, J. Mak, R. M. Oldenbeuving, M. Hoekman, D. Geskus, C. G. Roeloffzen, and K.-J. Boller, "Hybrid integrated InP - Si3 N4 diode laser with a 40-Hz intrinsic linewidth," Opt. Express **28**(15), 21713–21728 (2020).
17. C. Luo, R. Zhang, B. Qiu, and W. Wang, "Waveguide external cavity narrow linewidth semiconductor lasers," J. Semicond. **42**(4), 041308 (2021).
18. T. E. Drake, J. R. Stone, T. C. Briles, and S. B. Papp, "Thermal decoherence and laser cooling of Kerr microresonator solitons," Nat. Photonics **14**(8), 480–485 (2020).
19. F. Lei, Z. Ye, and V. Torres-Company, "Thermal noise reduction in soliton microcombs via laser self-cooling," Opt. Lett. **47**(3), 513–516 (2022).
20. Q. Zhang, B. Liu, Q. Wen, J. Qin, Y. Geng, Q. Zhou, G. Deng, K. Qiu, and H. Zhou, "Low-noise amplification of dissipative kerr soliton microcomb lines via optical injection locking lasers," Chin. Opt. Lett. **19**(12), 121401 (2021).
21. J. Wang, T. Jia, S. Wang, T. Li, C. Ma, T. Xie, Y. Yu, and J. Yu, "Wavelength synchronization technology for udwdm-pon transmitter based on injection locking," Chin. Opt. Lett. **19**(1), 010602 (2021).
22. X. Xue, Y. Xuan, P.-H. Wang, Y. Liu, D. E. Leaird, M. Qi, and A. M. Weiner, "Normal-dispersion microcombs enabled by controllable mode interactions," Laser Photonics Rev. **9**(4), L23–L28 (2015).
23. K. Nishimoto, K. Minoshima, T. Yasui, and N. Kuse, "Investigation of the phase noise of a microresonator soliton comb," Opt. Express **28**(13), 19295–19303 (2020).
24. G. Huang, E. Lucas, J. Liu, A. S. Raja, G. Lihachev, M. L. Gorodetsky, N. J. Engelsen, and T. J. Kippenberg, "Thermorefractive noise in silicon-nitride microresonators," Phys. Rev. A **99**(6), 061801 (2019).
25. F. Lei, Z. Ye, A. Fülöp, and V. Torres-Company, "Fundamental optical linewidth of soliton microcombs," arXiv preprint arXiv:2102.05517 (2021).
26. B. Y. Kim, Y. Okawachi, J. K. Jang, M. Yu, X. Ji, Y. Zhao, C. Joshi, M. Lipson, and A. L. Gaeta, "Turn-key, high-efficiency Kerr comb source," Opt. Lett. **44**(18), 4475–4478 (2019).