High temperature stability, low coherence and low relative intensity noise semiconductor sources for interferometric sensors

TIN KOMLJENOVIC* AND JOHN E. BOWERS

Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA

*tkomljenovic@ece.ucsb.edu

Abstract: We investigate self-seeded optical sources for interferometric sensing applications and show that they can, depending on optical filter bandwidth, provide high-output power, high wavelength temperature stability (<5 ppm/°C), low relative intensity noise (<-140 dBc/Hz) and low coherence lengths (<100 um). We characterize the key performance indicators for a range of optical filter bandwidths and provide insight into key design parameters of such sources for interferometric sensors.

© 2016 Optical Society of America

OCIS codes: (280.4788) Optical sensing and sensors; (030.1640) Coherence; (250.5960) Semiconductor lasers.

References and links

1. J. C. Wyant, “White light interferometry”, in Proceedings of SPIE 4737, Holography: A Tribute to Yuri Denisyuk and Emmett Leith (SPIE, 2002), pp. 98–107.
2. H. C. Lefevre, The Fiber-Optics Gyroscope (Artech House, 2014).
3. V. Vali and R. W. Shorthill, “Fiber ring interferometer,” Appl. Opt. 15(5), 1099–1100 (1976).
4. S. W. Lloyd, S. Fan, and M. J. F. Digonnet, “Experimental observation of low noise and low drift in a laser-driven fiber optic gyroscope,” J. Lightwave Technol. 31(13), 2079–2085 (2013).
5. T. Komljenovic, M. A. Tran, M. Belt, S. Gundavarapu, D. J. Blumenthal, and J. E. Bowers, “Frequency modulated lasers for interferometric optical gyroscopes,” Opt. Lett. 41(8), 1773–1776 (2016).
6. P. F. Wysocki, M. J. F. Digonnet, B. Y. Kim, and H. J. Shaw, “Characteristics of Erbium-doped superfluorescent fiber sources for interferometric sensor applications,” J. Lightwave Technol. 12(3), 550–567 (1994).
7. R. P. Moeller and W. K. Burns, “1.06-microm all-fiber gyroscope with noise subtraction,” Opt. Lett. 16(23), 1902–1904 (1991).
8. E. Wong, K. L. Lee, and T. B. Anderson, “Directly modulated self-seeding reflective semiconductor optical amplifiers as colorless transmitters in wavelength division multiplexed passive optical networks,” J. Lightwave Technol. 25(1), 67–74 (2007).
9. T. Komljenovic, D. Babić, and Z. Sipus, “47-km 1.25-Gbps transmission using a self-seeded transmitter with a modulation averaging reflector,” Opt. Express 20(16), 17386–17392 (2012).
10. A. Maho, G. Simon, S. Barbet, F. Lelarge, F. Salou, P. Chaneul, P. Parolari, L. Marazzi, M. Brunero, M. Martinelli, S. A. Grebewold, J. Leuthold, and R. Brenot, “Demystification of the self-seeded WDM access,” J. Lightwave Technol. 34(2), 776–782 (2016).
11. M. H. Reeve, A. R. Hunwicks, W. Zhao, S. G. Methley, L. Bickers, and S. Hornung, “LED spectral slicing for single-mode local loop applications,” Electron. Lett. 24(7), 389–390 (1988).
12. J. S. Lee, Y. C. Chung, and D. J. DiGiovanni, “Spectrum-sliced fiber amplifier light source for multichannel WDM applications,” IEEE Photonics Technol. Lett. 5(12), 1458–1461 (1993).
13. M. Presi and E. Ciaramella, “Stable self-seeding of Reflective-SOAs for WDM-PONs,” in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011 (2011), paper OMP4.
14. M. Presi, A. Chiuchiarelli, R. Corsini, and E. Ciaramella, “Uncooled and polarization independent operation of self-seeded Fabry-Pérot lasers for WDM-PONs,” IEEE Photonics Technol. Lett. 24(17), 1523–1526 (2012).
15. S. Ø. Dúill, L. Marazzi, P. Parolari, R. Brenot, C. Koos, W. Freude, and J. Leuthold, “Efficient modulation cancellation using reflective SOAs,” Opt. Express 20(26), B587–B594 (2012).
16. L. Marazzi, A. Boletti, P. Parolari, A. Gatto, R. Brenot, and M. Martinelli, “Relative intensity noise suppression in reflective SOAs,” Opt. Commun. 318, 186–188 (2014).
17. S. A. Grebewold, L. Marazzi, P. Parolari, R. Brenot, S. P. O. Duill, R. Bonjour, D. Hillerkuss, C. Hafner, and J. Leuthold, “Reflective-SOA Fiber Cavity Laser as Directly Modulated WDM-PON Colorless Transmitter,” IEEE J. Sel. Top. Quantum Electron. 20(5), 503 (2014).
18. M. Martinelli, “Time reversal for the polarization state in optical systems,” J. Mod. Opt. 39(3), 451–455 (1992).
19. J. Nayak, “Fiber-optics gyroscopes: from design to production [Invited],” Appl. Opt. 50(25), E152–E161 (2011).
1. Introduction

Low-coherence sources are used in a number of interferometric sensor applications to obtain high resolution optical images [1] or to measure different physical quantities such as rotation in interferometric fiber optic gyroscopes (IFOG). The use of a low-coherence source is either a key property that allows measurement or is a property that allows for superior performance due to significant reduction of coherent related impairments, such as reflections and backscatter, or polarization and non-linear related effects as in IFOG [2].

Traditionally, low-coherent sources used in IFOGs were based on superluminescent diodes (SLED) or erbium-doped fibers (EDF), and sometimes Fabry-Pérot (FP) lasers biased below threshold as a low-cost solution. Early approaches employed laser sources [3], but it was soon realized that the interference between various parasitic waves severely limits the performance [2]. Recently the use of lasers has been reconsidered. It was shown that lasers of high spectral purity can provide lower noise levels, commonly expressed as angular random walk (ARW), but still suffer from higher bias instability [4]. Fast frequency-modulation of lasers was shown to be a viable technique to improve bias stability, but the end performance still cannot match the performance of an IFOG driven by a broadband optical source [5].

SLEDs offer very low coherence levels due to their broad spectrums (3 dB bandwidths of more than 30 THz are available, depending on central wavelength of operation) and relatively high output powers. The relative intensity noise (RIN) of SLEDs can also be low due to the very large optical bandwidths. The RIN for thermal and pseudo-thermal sources scales as the inverse of the spectrum frequency width $\Delta f_{\text{FWHM}}$.

$$\text{PSD}_{\text{RIN}} = \frac{1}{\Delta f_{\text{FWHM}}}$$

A limitation arises due to high SLED sensitivity to temperature. The output power reduces with increased temperature. Provided that the output power is sufficient, a monitor tap can usually compensate for the change in power. A bigger issue is the change of the central operating wavelength due to the temperature. Precise wavelength is necessary in an IFOG as frequency is used to measure time of flight differences in counterpropagating beams. The phase difference $\Delta \Phi_{R}$ is often expressed as:

$$\Delta \Phi_{R} = \frac{2\pi LD}{\lambda c} \Omega$$

where $D$ is the coil diameter, $L$ is the fiber coil length, $\Omega$ is the rotation rate, $\lambda$ is the mean wavelength of the light source and $c$ is the speed of light. To control the wavelength of SLED sources, temperature control and stable driving current are needed. But even with temperature and power control, stability is in the 100 ppm range [2]. FP lasers below threshold operate very similarly to a SLED, with the addition of a larger spectral ripple that translates in more pronounced secondary coherence peaks, potentially lowering the performance.

EDF based, or in general rare-earth element based, sources provide much higher wavelength stability. Wavelength stability is typically below 20 ppm/$^\circ$C, and by careful optimization of fiber length and pump operating wavelength and power, even stabilities of 1 ppm with active temperature control have been demonstrated in limited temperature range in laboratory conditions [6]. The added benefits of EDF based sources are high output powers.
and unpolarized emission. The spectrum of EDF is very asymmetrical, with equivalent bandwidth equal to ~2.5 THz. This translates to increased coherence length (compared to SLED) and higher RIN of around ~124 dBc/Hz. High RIN is especially limiting, as due to high available output power, systems using EDF sources are often RIN limited. RIN suppression or compensation can be used [7].

To stabilize the wavelength in a wider temperature range, spectral filtering with stable filters can be employed both for SLED and EDF based sources. Filtering can significantly improve wavelength stability, but at the same time results with increased coherence length, higher RIN (due to narrower optical spectra) and reduction of power.

Here we propose an improvement to the spectral filtering approach, by introducing a new kind of optical source for such interferometric sensors that allows for controlled tradeoff between wavelength stability and coherence length, while suppressing RIN and reducing the filtering losses at the same time. The approach is based on long cavity lasers that have been explored as an optical source in wavelength-division-multiplexing passive-optical-networks (WDM-PON) [8–10]. In a WDM-PON, narrow-linewidth is favored for at least two reasons: lower dispersion penalties and tighter packing of channels so standard dense WDM channel spacing of 200, 100 and 50 GHz was explored. Here we investigate suitability of these configurations for low-coherence interferometry, but also expand our analysis to much wider filtering bandwidths that promise shorter coherence lengths.

2. RSOA based optical sources

A basic building block of considered sources is a reflective semiconductor optical amplifier (RSOA). RSOA is in a sense similar to an SLED with the exception that the back facet is made highly reflective, compared to an SLED where the back facet reflection is reduced as much as possible to prevent lasing due to potential feedback.

![Fig. 1. (a) Measurement setup (PD – monitor photodiode) (b) Output power and mean wavelength vs temperature at 120 mA bias current (c) Output power as a function of bias current for various temperatures (in 5 °C steps) (d) Optical spectrum at 120 mA of bias current for various temperatures (in 5 °C steps).]

In both cases, the front facet is optimized for low reflectance. SLEDs are, in general, due to high levels of gain, very susceptible to feedback. Feedback can cause performance changes and degrade device reliability. RSOAs in contrast are ideally operated under relatively strong...
feedback that results in lasing. We start our study with characterization of RSOA performance under different temperatures. The RSOA (InPhenix IPRAD1501) is packaged in a 14-pin butterfly package that includes a TEC element and a calibrated thermistor. This is a polarization independent RSOA with typical small signal gain of 18 dB and typical polarization dependant gain (PDG) of 1 dB. During measurements we swept the temperature between 10 °C and 60 °C, while keeping the temperature fluctuations below 0.05 °C with a precision temperature controller. The measurement setup is shown in Fig. 1(a). Figure 1(b) shows the output power and mean wavelength change as a function of temperature. The output power changes by $-0.37 \text{ dB/°C}$ (linear interpolation) while the mean wavelength (calculated as the power-weighted mean wavelength) changes by as much as 1.06 nm/°C which is higher than typically expected. It is unclear why the sensitivity is greater than expected, but it only servers to better illustrate the benefits of self-seeding in providing more temperature stable sources. Figures 1(c) and 1(d) give further insight in LI characteristics and output spectrum shapes at various operating temperatures. Due to the very broad emission spectra, the RIN is relatively low at $-129.5 \text{ dBc/Hz}$ (at 20 °C and 120 mA bias) and the coherence is extremely low at 20 µm (defined for coherence function visibility reduction to 0.8). There is a secondary coherence peak with 1% visibility at ~5 mm length in free space, corresponding to approximately 600 µm between the back and front facets on chip. We show a comparison between the coherence functions, including the RSOA, in Fig. 4.

3. Spectral-slicing vs self-seeding sources

Spectral slicing as a means to precisely define the operating wavelength has been studied in detail in communication systems [11,12] and the same approach can be applied in sensor applications. The precisely defined ITU grid in a DWDM communication channel stimulated development of extremely stable filters. It is common to have filters with wavelength stability better than 0.002 nm/°C or athermal arrayed waveguide gratings with wavelength stability better than 50 pm in a 70 °C temperature range. While improving the wavelength stability, filtering negatively impacts the output power by decreasing it, and negatively impacts the RIN and the coherence by increasing them.

Self-seeding allows for recovering most of the power and for RIN reduction while trading a bit in terms of wavelength stability and coherence length compared to spectrally-sliced sources, as we demonstrate. The self-seeding essentially changes a broadband spectrally-
sliced source to a lasing source, and allows for concentration of optical power inside the optical filter bandwidth.

Measurement setups for both source architectures are shown in Fig. 2. In both cases we use 1% tap couplers to monitor the output and feedback power. We used a number of bandpass filters (BPF) with varying bandwidths (0.22 nm, 0.5 nm, 8 nm, 13 nm, 37 nm) and compare them to the unfiltered case.

The self-seeding configuration has an added coupler used to split the light between the output and the seeding part. The coupler (50% coupling in Fig. 3(b)) can be used to control the level of feedback with output power being a dependant variable. We explore the effect of feedback strength in Section 4.1. The total cavity length in the self-seeding configuration, when comparing it to the spectral slicing configuration, was approximately 8 m. In the following measurements, we utilized a Faraday rotating mirror (FRM) to close the laser cavity. The FRM rotates the feedback by 90° which was shown to stabilize the output even in case of moderate PDG [13]. We return to polarization rotation in Section 4.2 where we also study the effect of cavity length. In the case of high-PDG RSOAs, injection of the orthogonal polarization will not provide lasing and use of an additional in-line Faraday rotator was proposed [14].

3.1 Key performance indicators

The key performance indicators of a particular configuration are summarized in Fig. 3. We report output power, mean wavelength change due to temperature, RIN and the coherence length.

![Graphs showing key performance indicators](image)

Filtering in the case of spectrally sliced sources results with significant output power reduction; up to 26 dB for narrowest filter with 0.22 nm bandwidth as shown in Fig. 3(a). Self-seeding is capable of recovering most of the power lost due to the filtering with maximum power loss equal to only 3.3 dB in case of a 0.22 nm filter. The losses are even lower in the case of larger bandwidth filters. Spectral filtering also increases RIN as predicted with Eq. (1). Self-seeding, due to the gain suppression of RSOA, allows for almost 15 dB
improvement in terms of RIN irrespective of the width of the spectral filter as shown in Fig. 3(c). Here we report RIN measured at frequency of 200 MHz. Narrowest configuration (0.22 nm filter) has RIN at $-124$ dBc/Hz, comparable with standard EDF based sources whose spectral width is in the range of 20 nm. For comparison, the spectrally-sliced RIN with same optical bandwidth is $-111$ dBc/Hz. We plot RIN at $T = 25^\circ C$ (while output power and coherence length are plotted for $T = 20^\circ C$), as in some configurations RIN for self-seeded configuration increases at $T = 20^\circ C$ due to strong feedback. As the RIN suppression is dependent on the feedback level, we study the said effect in more detail in Section 4.1 showing that this is not an issue for a properly designed self-seeded source. We also show RIN at low frequencies in Section 4.2. Self-seeding improves both the output power and the RIN performance, but results with somewhat lower temperature dependant wavelength stability and longer coherence lengths compared to the spectrally-sliced sources. Nevertheless it substantially improves, up to more than two orders of magnitude, the wavelength temperature stability compared to the unfiltered case as shown in Fig. 3(b). For testing the sensitivity to the temperature change, we heated only the RSOA for simplicity. In practical application the whole extended cavity would be heated, and the filter temperature drift would also influence the performance. Commercial filters used for testing are quoted with drifts as low as <0.002 nm/°C, so that the filter stability by itself would limit the wavelength stability only in the case of spectrally sliced narrow bandwidth configurations. We signal that point with a horizontal dashed black line in Fig. 3(b) corresponding to the filter wavelength stability. The wavelength stability of the RSOA by itself is around 680 ppm/°C. Self-seeded transmitters using filters with 0.5 nm and 0.22 nm bandwidth offer stability of 8 ppm/°C or 2.66 ppm/°C in the temperature range of 10-35 °C. We specify stability only up to 35 °C due to RSOA not having enough gain at elevated temperatures to compensate for extended cavity losses. We address that point in more detail in Section 4.

![Fig. 4. (a) Unfiltered RSOA (b) Spectrally-sliced, 13 nm optical bandwidth (c) Spectrally sliced, 0.22 nm optical bandwidth (d) Self-seeded without filter (e) Self-seeded, 13 nm optical bandwidth (f) Self-seeded, 0.22 nm optical bandwidth.](image)

To simplify the measurements of coherence functions, we employed an optical spectrum analyzer (OSA) and utilize the fact that the coherence (or auto-correlation) function is the inverse Fourier transform of the centered intensity spectrum [2]. The method as applied here has some limitations, mainly the resolution limitation of the OSA (2.5 GHz) and the number of points we sampled (10,000). The resolution limits the timescale at which we can study the coherence length, but it manifests itself at long timescales (path differences) which are of less interest with low-coherence sources. The number of points define the resolution of our path difference plots, and this is not a limiting factor in our measurements. Some illustrative
coherence functions are plotted in Fig. 4 covering the two extremes (no-filtering and narrow filter) as well as an in-between configuration, and from such plots we extract a single number that we plot as coherence length in Fig. 3(d). We define the coherence length as path difference at which the coherence function reduces to 0.8. Self-seeding increases the coherence length by a factor of 1.5-4 compared to spectral slicing, but still provides coherence lengths in mm to sub-mm range which is superior even to the frequency modulated lasers [5] whose coherence lengths are in the cm range.

4. Detailed performance specific considerations

In this section we address in more detail some peculiarities of spectrally-sliced and self-seeded optical sources. First we touch upon the wavelength stability of spectrally-sliced sources that is dependent on the filter bandwidth. Hastily one might conclude that provided that the filter stability is the same, the mean wavelength shouldn’t change irrespective of the filter bandwidth, but that is obviously not the case as seen in Fig. 3(b). The reason is that the shape of the optical spectrum changes, and that consequently influences the mean wavelength as shown in Fig. 5(a). Here we have plotted the 37 nm filter case, as it most clearly illustrates the change of mean wavelength despite using a very stable filter. Interestingly, self-seeded sources actually offer superior wavelength stability when there is no filtering, or very comparable performance in cases the filter bandwidth is very large (e.g. 37 nm).

We show a typical light-current (LI) characteristic of a self-seeded source in Fig. 5(b). For lower temperatures, where the RSOA gain is higher, there is a clear threshold indicating laser operation. The extended cavity with 0.22 nm filter does not lase at temperatures higher than 35 °C and that is the reason we specify wavelength stability in Fig. 3(b) only between 10 °C and 35 °C. A higher gain RSOA, or reduced cavity losses would allow lasing at elevated temperatures.

Fig. 5. (a) Optical spectrum of spectrally-sliced source using filter with 37 nm of bandwidth (b) LI curves for self-seeded source with 0.22 nm filter. Threshold is clearly observed at lower temperatures as well as the absence of lasing at temperatures higher than 35 °C (c) Optical spectrum of self-seeded source with 13 nm filter shows lasing up to 45 °C (d) Optical spectrum of self-seeded source with 0.22 nm filter shows lasing up to 35 °C.
The LI characteristic serves to explain as to why self-seeded configurations incur lower filtering losses, reason being the concentration of optical power on lasing modes. In Fig. 5(c) and 5d we show spectrums for self-seeded transmitters using 13 nm and 0.22 nm wide filters, again to show differences between narrow and wide optical filters. In both cases transition between just filtering and lasing is obvious. A wider filter configuration also lases at higher temperature, as the total loss (insertion and spectral filtering loss) of the filter is lower. Finally we plot all the optical spectrums at room temperature (20 °C) in Fig. 6.

4.1 Feedback and RIN

Gain saturation has widely been used to suppress RIN with both semiconductor optical amplifiers (SOA) and RSOAs. It was shown that SOA theory is not sufficient to explain the complexity of behavior present with RSOAs [15], the reason being the two waves propagating in the opposite directions competing for gain. RSOAs therefore have three nonlinear operation regimes due to the saturation effect. For weak feedback the signal (and noise) is moderately bleached, for medium feedback signals the suppression is optimal and then, due to strong depletion at high feedback levels, signal inversion occurs. As the same mechanism, compression, is used to suppress RIN, it is expected that noise suppression becomes less efficient at very high feedback levels. The measurements agree well with theoretical predictions and indeed show that RIN increases at high feedback levels, especially at low frequencies [16].

Measurements in [16] utilized a 0.43 nm wide filter. Here we repeat similar measurements, but with a wider 13 nm filter as such configuration has not been studied previously. The measurement setup is shown in Fig. 7(a). In order to allow for high levels of feedback we change the seeding coupler to a 10:90, and connect the 90% port to the FRM. In between we place a variable attenuator. We use two kinds of attenuators. A computer controlled one is used to precisely vary the feedback levels at lower feedback levels, but due to insertion loss of 4 dB, we switch to a manual one at higher feedback levels. The two regimes are marked with auto and manual in Fig. 7(b). We include a theoretical prediction of RIN (−122 dBc/Hz) for a pseudo-thermal source of same spectral width (dashed horizontal
black line). The measurements are performed with HP 71400C lightwave signal analyzer that automatically corrects for thermal and shot noise contributions to RIN.

![Fig. 7. (a) Setup for measuring feedback level effect on RIN (b) Feedback level vs RIN at three frequencies. Dashed horizontal black line show the theoretically expected RIN level for pseudo-thermal lightsource of equal bandwidth.](image)

It is interesting to note that at lower feedback levels, the RIN actually increases due to feedback compared to pseudo-thermal source of the same spectral width, possibly suggesting chaotic behavior. With increase of feedback, the RIN steadily decreases down to the levels of $-133$ dBc/Hz providing an improvement of 11 dB compared to spectral slicing and then again quickly increases once feedback reaches a certain threshold. But noise spectral behavior is distinctly different between low and high levels of feedback. In the case of low feedback, noise is mostly flat in the considered range of frequencies, while in the case of high feedback, the increase in noise is much more pronounced at lower frequencies. In a practical self-seeded source for interferometric sensors, the level of feedback can directly be controlled with the selection of the output coupler, and using lower split levels for feedback will increase the available output power.

4.2 Feedback and RIN

In a WDM-PON system, the length of an extended cavity is not a design choice, as it is determined by the distance between the end-used and the remote node. For typical WDM-PON networks the lengths are in hundreds of meters, or even a few kilometers. In a potential sensor application, the length of extended cavity can be optimized. The length is expected to have a direct effect on RIN due to the beating of longitudinal modes.

For measuring the low frequency noise, we employ a different setup. The input optical power is controlled by an attenuator and is kept the same between the measurements ($-7.5$ dBm) allowing for a direct comparison. The optical signal is converted to electrical with a DC coupled photodetector (Agilent 11982A Lightwave Converter) whose output is fed to an Agilent 4396B spectrum analyzer via a 7 kHz DC block (Picosecond Pulse Labs 5501A). In all measurements we also include the noise floor measured with no light incident to the photodetector, showing that RIN is generally below the noise floor except at beat lengths corresponding to the extended cavity length. We show two illustrative configurations in Fig. 8. Figure 8(a) shows noise performance of approximately 8 m long cavity defined by the length of fiber pigtails of components used to form the cavity. In Fig. 8(b) we add a spool of fiber increasing the total cavity length to approximately 202 m. We use two filter bandwidths: 0.22 nm and 13 nm once again to show potential differences between commonly studied narrow filter self-seeded configurations and wider filter configurations with much reduced coherence lengths. The cavity is terminated by either FRM or a fiber mirror (FM). FRM is used, as was already pointed out, to stabilize the output due to potential polarization dispersion and PDG of the RSOA, but it also changes the effective cavity length in our case. Despite having a RSOA with low PDG, it seems that it predominantly lases on one
polarization so the effective cavity length doubles as evident from the mode spacing in Fig. 8. The mode spacing also allows us to easily measure the length of the cavity. The filter bandwidth and the extended cavity length control the number of longitudinal modes. For short cavity and narrow filter, the number of longitudinal modes is in the few thousands. This number increases to a few millions of modes for a longer cavity with a wider filter. As the number of modes increase, the peak height decreases, and the modes in general seem to be more pronounced in case polarization rotation is used. The former effect can be related to the chromatic dispersion [17] and the latter to the time-reversal of polarization state property of the FRM [18].

In the case of interferometric gyroscope application, the rotation signal is usually extracted at the gyroscope proper frequency and, in some cases, its few higher harmonics [2]. The proper frequency \( f_p \) is determined by the gyroscope coil length or more precisely the group transit time \( \Delta \tau_g \) through the coil.

\[
f_p = \frac{1}{2 \Delta \tau_g}. \tag{3}
\]

Typical lengths of coils are between 100 and 3000 m [19], placing the proper frequency between 30 kHz and 1 MHz. The ability to freely chose the extended cavity length allows us to tailor the RIN spectra so that the gyroscope signal does not overlap with RIN peaks due to the longitudinal modes. This means that the extended cavity should be significantly shorter than the gyroscope coil, which is easily achieved in practice. Due to pigtail lengths we were limited to measuring down to ~8 m of cavity length. With removal of the tap coupler and by splicing all of the components with very short pigtails ~1 m cavity lengths should be attainable. Monolithic integration allows for even shorter cavity lengths using ultra-low-loss Si\(_3\)N\(_4\) waveguides [20]. With the reduction of extended cavity length, the number of longitudinal modes decreases and a further study of the effects on the performance is needed.

5. Conclusion

We introduce the concept of self-seeded optical source for interferometric applications. Self-seeding, as an extension of previous spectral-slicing approaches that were considered both for communication and sensing applications, allows for higher output powers with less than 4 dB of loss due to filtering, irrespective of the optical filter bandwidth and lower relative intensity noise by a factor greater than 10 dB. At the same time self-seeding significantly increases the wavelength stability compared to the unfiltered semiconductor based broadband optical sources (~400-650 ppm/°C) typically used in optical gyroscopes, bringing it to <5 ppm/°C ranges without active temperature control.
Self-seeded optical sources have been studied in depth with narrow optical filters, primarily for application in wavelength division multiplexed passive optical networks. Here we expand the study to wider optical filter bandwidths and show that the filters allow us to control the source coherence length which can be crucial for some applications such as interferometric fiber optic gyroscopes or other types of sensors based on Sagnac loops such as current or magnetic sensors. We demonstrate coherence lengths in mm and sub-mm range. This approach can be integrated onto a chip using heterogeneous silicon sources integrated with low loss silicon nitride waveguides with lengths of tens of meters [20–22].

**Funding**

DARPA MTO (iWOG HR0011-14-C-0111); Croatian ministry NEWFELPRO (no. 25).

**Acknowledgments**

The authors thank Robert Lutwak and Dan Blumenthal for useful discussions. This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.