Letter Vol. 41, No. 8 / April 15 2016 / *Optics Letters* 1773

Optics Letters

Frequency modulated lasers for interferometric optical gyroscopes

Tin Komljenovic,* Minh A. Tran, Michael Belt, Sarat Gundavarapu, Daniel J. Blumenthal, and John E. Bowers

Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA
**Corresponding author: tkomljenovic@ece.ucsb.edu*

Received 17 February 2016; revised 10 March 2016; accepted 15 March 2016; posted 15 March 2016 (Doc. ID 259267); published 8 April 2016

We study the use of frequency modulated lasers in interferometric optical gyroscopes and show that by exploiting various frequency modulation signals, the laser coherence can be controlled. We show that both angle random walk and bias stability of an interferometric optical gyroscope based on laser sources can be improved with this technique.

OCIS codes: (060.2800) Gyroscopes; (280.4788) Optical sensing and sensors; (030.1640) Coherence; (250.5960) Semiconductor lasers.

http://dx.doi.org/10.1364/OL.41.001773

The fiber optic gyroscope has become, arguably, the most commercially successful optical sensor to date [1]. Early approaches employed laser sources [2], but researchers soon realized that broadband sources with shorter coherence lengths significantly improved the performance of interferometric fiber optical gyroscopes (IFOG). Using sources with short coherence lengths significantly suppresses the interference between various parasitic waves generated in the system due to backreflection, backscattering, and Kerr nonlinearity which, in turn, leads to reduced noise and improved system performance [3]. Therefore, IFOGs have generally utilized superluminescent diodes (SLED) or erbium-doped fiber (EDF)-based sources for medium- and high-performance gyroscopes [3,4] and, sometimes, Fabry–Pérot (FP) lasers biased below threshold as a low-cost solution. EDF-based sources generally offer the best performance, primarily due to higher temperature stability but, at the same time, are more costly and harder to package. Recently, the use of single-frequency lasers with high-spectral purity has been considered as an alternative to broadband sources [5]. A single-frequency laser source does not suffer from excess noise and can achieve higher scale factor stability due to a greater degree of wavelength stability. The authors show that through a careful selection of laser coherence (narrow linewidth) and adoption of the push-pull phase modulation technique (common in most modern IFOG setups), a better (lower) resolution limit can be achieved, although at the expense of higher drift.

In this Letter, we explore the use of high-speed frequency modulated (FM) lasers in interferometric optical gyroscopes. We show that frequency modulation of both single-frequency and FP lasers is a useful technique to control source coherence length and improve gyroscope performance simultaneously. FM modulation in conjunction with gyroscopes has received relatively little attention. Cutler *et al.* suggested that a fast change in source frequency can reduce the errors due to Rayleigh scattering [6], and Culshaw and Giles investigated heterodyne detection of FM-modulated laser light in an IFOG primarily to overcome 1/f noise problems [7]. More recently, Blin *et al.* investigated high spectral purity frequency-modulated lasers in IFOGs and concluded that fast sweeping of laser source frequency can reduce backscatter noise by offsetting the signal and backscattered noise in frequency [8]. Here, we go a step further, showing that more complex FM modulation signals can result in even larger improvements in overall gyro performance when using commercial off-the-shelf lasers as optical sources. We relate the FM-modulated signals to their corresponding coherence functions and show that by optimizing the source coherence functions, we can clearly improve both the angular random walk (ARW) and the bias drift performance.

Our primary motivation in using high-speed FM-modulated lasers as optical sources results from our goal of full chip-scale integration of an interferometric optical gyroscope where the sensing coil would not be a fiber, but an integrated waveguide realized in ultra-low loss SiN waveguides [9,10], as shown in Fig. 1. We have presented preliminary results obtained with an integrated 3 m long Si_3N_4 waveguide coil in [12]. The main reasons to use a laser are higher output powers and lower noise (Fig. 2). With a laser resonant cavity, we can control the directionality of lasing output by deliberately adjusting mirror reflectivities.

The laser may be destabilized by the resulting gyroscope feedback, and require an isolator. Isolators have been demonstrated on the heterogeneous silicon platform [13], and may be required with either laser or ASE sources. The study and analysis of the influence of relatively strong feedback on laser operation in an integrated platform in the case when isolator is not present, together with the methods to optimize device performance, are currently underway and will not be discussed within the scope of this Letter.

We expect to improve both ARW and bias drift performance with reduction of the coherence length due to FM modulation.

0146-9592/16/081773-04 Journal © 2016 Optical Society of America

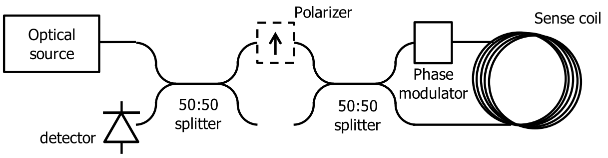

Fig. 1. Minimum configuration of a reciprocal optical Sagnac interferometer. The polarizer is optional as, in our fully integrated version, the waveguides exhibit very high polarization extinction ratios, eliminating the need for an additional polarizer [11].

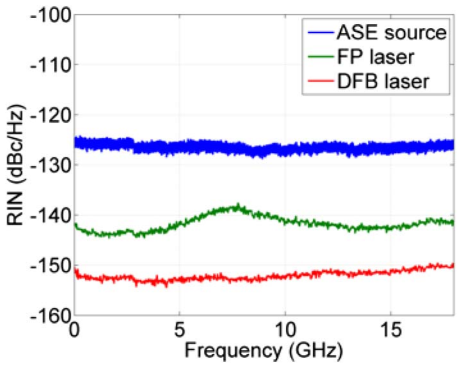

Fig. 2. RIN comparison between broadband source, single-frequency DFB and FP lasers.

At the same time, we expect to keep the lower relative intensity noise (RIN) and higher wavelength stability inherent to lasers, when compared to alternative semiconductor-based broadband optical sources. We expect a single-frequency laser to outperform an FP laser when comparing both the RIN and wavelength stability. The wavelength stability of an FP laser is dominated by the temperature-induced gain shift (typically around ~0.6 nm/°C at 1550 nm, similar to SLED), while the resonator that determines the operating wavelength of a distributed feedback (DFB) laser usually drifts by a rate of almost an order of magnitude slower for both InP- and Si-based resonators. This drift is characterized by the thermo-optic coefficient, which is approximately $2 \times 10^{-4}\ \mathrm{K}^{-1}$ around room temperature for both material systems. This leads to an approximate drift of ~0.08 nm/°C. As stated above, the use of lasers as optical sources in interferometric optical gyroscopes has been shown to be limited by excess noise and drift as a result of coherent backscattering, backreflection, and Kerr nonlinearity, all of which can be significantly suppressed by purposefully reducing the coherence of the source. Since a fully integrated approach has a very compact footprint and, thus, reduced effective area and scale factor, our target application space is that of rate grade gyroscopes (ARW $> 0.5^\circ/\sqrt{h}$ and bias drift of 10°/h), which can potentially be realized by exploiting lasers utilizing coherence control. With source coherence being so vital to overall system performance, we begin our analysis with an overview of the spectral characteristics of standard, widely available lasers.

We study both single-frequency and FP lasers for use in a fully integrated laser gyroscope. To explain the improvements in interferometric optic gyroscope performance through the application of FM modulation, we turn to the coherence functions, $C(\tau)$, of the sources.

To simplify the measurements of coherence functions of various ranges (from ~10 m down to single-digit centimeters), we employed a high-resolution optical spectrum analyzer (OSA) with 20 MHz resolution, and utilized the fact that the coherence (or auto-correlation) function is the inverse Fourier transform of the centered intensity spectrum [3]. As applied here, the method has some limitations, such as the resolution limitation of our OSA and the omission of potential spectral asymmetry but, nevertheless, serves to illustrate the method through which the complex FM modulation signals reduce the backscatter related noise and improve gyroscope performance. All the considered sources operate around a 1550 nm range, and the measured mean wavelengths (λ_c) are given in Table 1.

We begin with a commercially available DFB laser. The measurement of the coherence length of the unmodulated DFB laser is limited by the OSA, as the linewidth is specified as narrower than 20 MHz, so its coherence length is underestimated in Fig. 3. In this case, we have also used the delayed self-heterodyne method to measure the coherence length. Measured full-width half-maximum linewidth is 3.28 MHz, and the corresponding coherence is plotted in dashed lines, assuming a purely Lorentzian spectrum. We compare this coherence length to the resulting coherence lengths when the laser is modulated by a single frequency (300 MHz) tone and when we modulate the laser with two frequencies whose ratio is not an integer value (300 MHz and 99 MHz). The corresponding spectra and coherence functions are shown in Fig. 3. We can see that the modulation allows for a reduction of coherence length by a minimum of two orders of magnitude, as the continuous-wave laser coherence is underestimated, as described above. In the case of single-tone modulation, there is a coherence peak around

Table 1. Key Performance Indicators for ASE and Laser-Based Gyroscope Measurements[a]

Source Type	Laser Drive Frequency (MHz)	Optical Power (dBm)	Scale Factor (V/[deg/s])	ARW (deg/sqrt[h])	Bias Instability (deg/h)
ASE ($\lambda_c = 1545.62$ nm)	N/A	−6.1	1.23	0.061	0.399
FP Laser	CW	−6.1	1.3	0.075	4.518
($\lambda_c = 1554.38$ nm)	300	−6.1	1.29	0.033	1.953
	300, 110	−6.1	1.22	0.037	2.055
DFB Laser	CW	−6.1	1.2	0.048	2.885
($\lambda_c = 1548.92$ nm)	300	−6.1	1.2	0.037	1.723
	300, 110	−6.1	1.2	0.033	1.431

[a] FM modulation improves both the ARW and the bias instability.

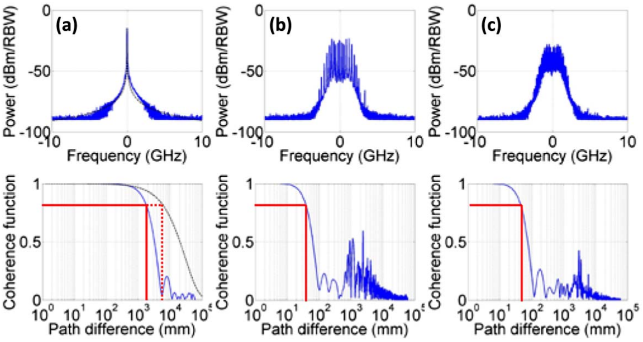

Fig. 3. Measured spectra and corresponding coherence function for a DFB laser. The three rows correspond to (a) continuous-wave (coherence length $L_c = 6536$ mm, measured with self-heterodyne method); (b) single-tone modulation (300 MHz, $L_c = 42$ mm); and (c) two-tone modulation (300 and 99 MHz, $L_c = 48$ mm). Fast FM modulation allows for a reduction of the coherence length by approximately two orders of magnitude.

1 m, which corresponds to the applied 300 MHz signal. Two-tone modulation largely suppressed the coherence peak, further improving the gyroscope performance as shown in the next section. A single-tone modulation is similar to the sawtooth signal used in [8], and we show that more elaborate modulation signals can further improve performance. In theory, more complex modulation signals, such as pseudo-random sequences, could even further reduce the coherence function peaks at longer path differences, but care has to be taken that this added modulation does not introduce noise at frequencies close to the gyroscope signal (the sensing coil proper frequency and its harmonics).

FP lasers are another choice for an integrated gyroscope and, as a first guess, one might intuitively guess that multiple peaks in the lasing spectrum will further reduce the source coherence, consequently further improving eventual gyroscope performance.

Measured spectra and corresponding coherence functions of a typical commercial FP laser are shown in Fig. 4. The coherence function for a continuous-wave FP laser shows a number of coherence peaks separated by the longitudinal mode spacing and an envelope whose path distance is determined by the spectral linewidths of the individual modes. These FP results suffer from undersampling, as the high-resolution OSA has a limited number of data points it can take, and we have to take much wider traces to capture the majority of the longitudinal modes. Unfortunately, stitching together multiple measurements with a reduced span resulted in additional artifacts, further obscuring the results. The coherence function is truncated around 500 mm due to the large sample separation in the frequency domain, so the coherence peak that should correspond to 300 MHz modulation is not visible. Nevertheless, it is obvious that the coherence function is more complex and has interlocked minima and maxima. This will result in increased bias drift due to small changes within the sense coil due to, e.g., temperature changes as the backscatter signature drifts between the minima and maxima of the coherence function. Mode-hopping can also influence gyroscope performance due to the resulting change of mean wavelength. Such an effect would manifest itself primarily as a scale factor drift. Using FM modulation with an FP laser, one can reduce the path length difference of the envelope, similarly to reducing the coherence of the DFB laser. The envelope reduces due to an increase in linewidth of the individual modes, but the coherence peaks are still present, potentially resulting in bias drift. Direct modulation can hardly suppress the coherence peaks, as they are dictated by cavity length and usually separated by 50–150 GHz in common FP lasers. A possible route to reduce such peaks could be to design a laser with multiple gain sections and higher frequency deviation efficiency [14]. This is currently under investigation. This complex coherence function, together with a higher RIN and greater degree of thermal drift, indicates that the performance of a gyroscope utilizing an FM-modulated FP laser will be worse than one that utilizes an FM-modulated DFB laser.

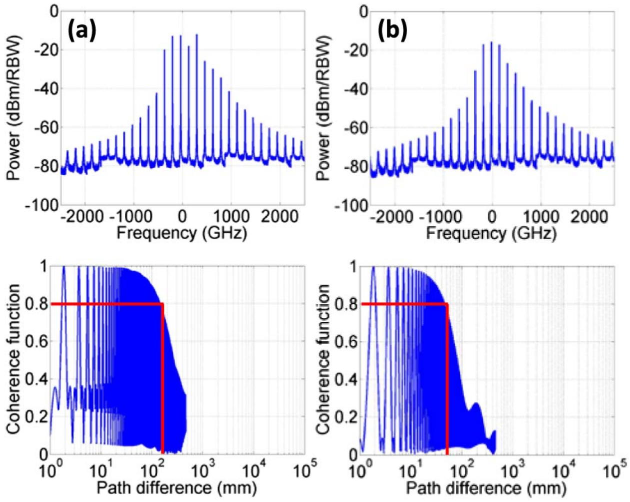

Fig. 4. Measured spectra and corresponding coherence function for an FP laser. The two rows correspond to (a) continuous-wave (coherence length $L_c = 145$ mm) and (b) single-tone modulation (300 MHz, $L_c = 47$ mm).

The performance of the various above-mentioned optical sources was quantified with a fiber-based optical gyroscope (Fig. 5). The use of a circulator prevented feedback to the optical sources and, as we noted above, the resulting effect of such feedback is currently under study and will be reported in a future publication. We implemented a simplified configuration, containing only a single commercial $LiNbO_3$-based phase modulator. An EDF-based broadband source was included as a baseline comparison. The lock-in amplifier had a 30 ms integration time with a 12 dB/octave roll-off corresponding

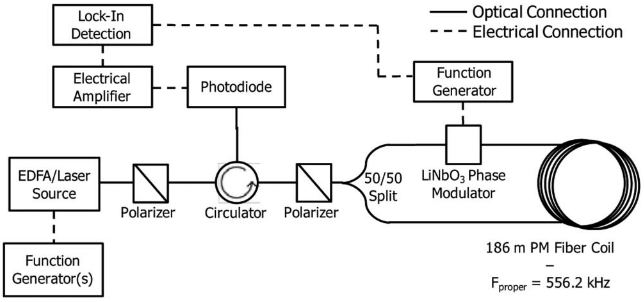

Fig. 5. Schematic of in-house assembled fiber-based optical gyroscope. All fibers after the first polarizer are PM, and input polarization is optimized for maximum power at the photodiode. The coil diameter is 20 cm. Each fiber component is connected to the next by an FC/APC connector.

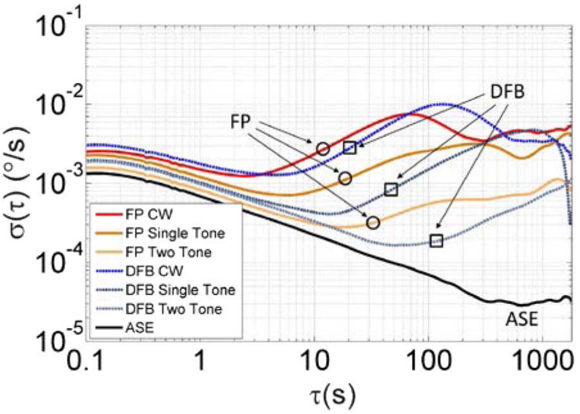

Fig. 6. Allan deviation measurements for each optical source at CW, single, and two-tone modulation. FM modulation improves both the ARW and bias stability in all cases.

to ~4 Hz bandwidth. The signal from the lock-in was sampled at 50 Hz.

Measurements of Allan deviation were performed over a period of 1 h, with the results plotted in Fig. 6. The results are each converted to °/s by measuring the gyroscope scale factor using a rotation table. We have included the best results for each configuration to illustrate that FM-modulated lasers can be serious candidates for an optical source in a fully integrated interferometric gyroscope. We should point out that the end performance is sensitive to external factors, such as temperature drift. From Fig. 6, we can see that the laser sources generally provide an ARW that is comparable to the ASE source, but suffer from much higher bias drift, which is in agreement with previous studies. This is to be expected as the coherence length of an EDF-based ASE source is still shorter by approximately three orders of magnitude. Additionally, DFB lasers outperform FP lasers, which is consistent with our predictions from the previous section. FM modulation improves performance in all cases, and the two-tone modulation scheme further improves both the ARW and bias drift, compared to the single-tone modulation scheme. The reason for improved performance comes due to the reduction of the coherence length and suppression of secondary coherence peaks with more complex modulation signals. Key performance numbers are summarized in Table 1. In all cases, we applied direct laser modulation, but external modulation could also be utilized to the same effect of controlling coherence. Direct modulation in the considered cases results in spurious intensity modulation that further helps in the reduction of the coherence length of the source. Deeper modulation, resulting in more generated sidebands, can also be used to tailor the source coherence function.

We explored the use of high-speed frequency modulated (FM) lasers in interferometric optical gyroscopes and showed that frequency modulation of both single-frequency and FP lasers is a valuable technique to control source coherence length and, as a result, improve the performance of such laser-driven gyroscopes. Utilizing an in-house fiber-based gyroscope test bed, we showed that FM modulation improves both angular random walk (ARW) and bias drift, when compared to a CW laser implementation. We related this improvement in performance to coherence length reduction and showed that more complex FM modulation signals can further improve gyroscope performance. When directly comparing typical commercial FP and DFB lasers, we showed that DFB lasers offer superior performance due to inherently higher wavelength and output power stability.

Funding. Defense Advanced Research Projects Agency (DARPA) (HR0011-14-C-0111); NEWFELPRO (25).

Acknowledgment. The authors would like to thank Robert Lutwak for useful discussions. 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.

REFERENCES

1. B. Culshaw, Meas. Sci. Technol. **17**, R1 (2006).
2. V. Vali and R. W. Shorthill, Appl. Opt. **15**, 1099 (1976).
3. H. C. Lefevre, *The Fiber-Optic Gyroscope* (Artech House, 2014).
4. J. Nayak, Appl. Opt. **50**, E152 (2011).
5. S. W. Lloyd, S. Fan, and M. J. F. Digonnet, J. Lightwave Technol. **31**, 2079 (2013).
6. C. C. Cutler, S. A. Newton, and H. J. Shaw, Opt. Lett. **5**, 488 (1980).
7. B. Culshaw and I. P. Giles, IEEE Trans. Microwave Theory Tech. **30**, 536 (1982).
8. S. Blin, M. J. F. Digonnet, and G. S. Kino, Proc. SPIE **7004**, 70044X (2008).
9. J. F. Bauters, M. L. Davenport, M. J. R. Heck, J. K. Doylend, A. Chen, A. W. Fang, and J. E. Bowers, Opt. Express **21**, 544 (2013).
10. S. Srinivasan, R. Moreira, D. Blumenthal, and J. E. Bowers, Opt. Express **22**, 24988 (2014).
11. J. F. Bauters, M. J. R. Heck, D. Dai, J. S. Barton, D. J. Blumenthal, and J. E. Bowers, IEEE Photon. J. **5**, 6600207 (2013).
12. S. Gundavarapu, T. Huffman, R. Moreira, M. Belt, J. E. Bowers, and D. J. Blumenthal, *Optical Fiber Communication Conference* (2016), paper W4E.5.
13. M.-C. Tien, T. Mizumoto, P. Pintus, H. Kroemer, and J. Bowers, Opt. Express **19**, 11740 (2011).
14. J. E. Bowers, R. S. Tucker, and C. A. Burrus, IEEE J. Quantum Electron. **20**, 1230 (1984).