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The Macek and Davis experiment revisited: a large ring laser interferometer operating on the $2s^2 \rightarrow 2p^4$ transition of neon

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We operate a large helium–neon-based ring laser interferometer with single-crystal GaAs/AlGaAs optical coatings on the $2s_2 \rightarrow 2p_4$ transition of neon at a wavelength of 1.152276 µm. For either single longitudinal- or phase-locked multi-mode operation, the preferable gas composition for gyroscopic operation is 0.2 and 0.3 mbar of 50:50 neon with total pressures between 6–12 mbar. The Earth rotation bias is sufficient to unlock the device, yielding a Sagnac frequency of approximately 60 Hz. © 2019 Optical Society of America

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1. INTRODUCTION

Bi-directional ring lasers, capable of sensing an externally imposed physical rotation such as that provided by the Earth, have advanced significantly over the last three decades [1], both in their sensitivity and stability, as evidenced by the observation of low frequency effects such as the Chandler and annual wobbles of the rotating Earth [2]. To a significant degree (although not exclusively), this has been achieved through the use of advanced, ultra-low-loss mirrors and the development of active interferometers whose beam paths enclose ever larger areas. Indeed, laser gyroscopes have been constructed whose beam path encloses areas as large as 834 m^2 [3]. Although differing in their performance all large active Sagnac interferometers have the same general features, namely they all use a gaseous helium–neon-based gain medium which fills the entire optical cavity regardless of its dimensions with radio-frequency (RF) excitation occurring in a small (windowless) capillary. This has the desirable feature that the only intra-cavity optical elements are the mirrors which define the cavity itself. It is additionally notable that of the available optical transitions of the gain medium, the 632.8 nm ($3s_2 \rightarrow 2p_4$) neon transition has been used exclusively.

The first demonstration of rotation sensing using an active optical cavity was reported by Macek and Davis [4] as early as 1963, a few short years after the first demonstration of the laser itself. In their seminal experiment, Macek and Davis employed a 1 m^2 cavity having four sealed gain tubes, one located on each side of their square ring and therefore having 20 intra-cavity surfaces. Rotation sensing was achieved by means of a large mechanical turntable whose plane was orthogonal to the normal vector of the cavity. Interestingly, their laser operated on the $2s_2 \rightarrow 2p_4$ neon transition at 1.152276 µm (presumably because their actual experiment preceded the first reports of laser oscillation at visible wavelengths using the helium–neon gain medium) and this is unlike any device constructed more recently of comparable or larger dimensions.

As mentioned above, advances in the production of ultra-low-loss mirrors (so-called "supermirrors") have played a considerable role in the concomitant development of rotation sensing ring laser gyroscopes. As such, it is interesting to revisit the Macek and Davis experiment utilizing state-of-the-art mirrors and exploiting the knowledge gained through three decades of large-area ring laser development. Such an experiment is more than just a historical curiosity of course, since longer wavelength laser radiation should, in principle, decrease the backscatter amplitude (the scattering of the intra-cavity laser beams into the counter-propagating beam path) and therefore minimize the induced optical frequency perturbations. In a previous brief report, we have demonstrated the sensing of Earth rotation at an infrared wavelength [5]. Here, we describe a

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detailed investigation of the operational characteristics of a large ring cavity designed for operation at a laser wavelength of 1.152276 μm employing crystalline coated intra-cavity supermirrors.

2. EXPERIMENTAL DETAILS

We have performed our experiments using a vertically mounted 2.56 m^2 square ring laser (roughly 2.5 times larger in area than the Macek and Davis ring) located on the second floor of a high-rise building on the Ilam campus of the University of Canterbury in Christchurch, New Zealand. This device has been previously denoted as “PR1” in the literature (see Fig. 1). As with all of our laser systems, the entire cavity is filled with cold helium–neon gas and the only optical elements are the four 2 m radius of curvature intra-cavity, spherical supermirrors. In this particular case, RF excitation at 80 MHz occurs within a 4 mm diameter Pyrex tube having a length of 100 mm (RF excitation is used here to avoid Langmuir flow, which is an undesirable source of intra-cavity bias).

The details of the crystalline coated cavity mirrors have been reported previously and the reader is referred to [5,6] for more details. In brief, the end mirrors consist of 8 mm diameter GaAs/AlGaAs crystalline coatings transferred to 25 mm diameter, superpolished fused silica substrates, optimized for operation at a 45 deg angle of incidence having a designed transmission of 1.7 ppm for *s*-polarized light. In principle, these crystalline coated mirrors offer a reduction in thermal noise for high-sensitivity optical interferometry. Alignment of the ring cavity was performed using a combination of a handheld IR viewer, a near-infrared detector card, and the residual sensitivity of a silicon-based CCD camera installed at the lower right corner of the cavity looking at the counter-clockwise beam. A power meter with a germanium power sensor head is located at the top left corner of the cavity to monitor the output power of the laser. After optimum alignment was achieved, a fast photodetector was installed at the top right corner of the laser cavity to detect the counter-clockwise beam. The output of this photodetector was then fed into a servo system that stabilizes the laser output power. We employ a 50:50 non-polarizing beam splitter cube to combine the two counter-propagating beams, which were detected by a thermo-electrically cooled InGaAs photodetector. Continuous logging of both the combined beams and the single beam output was performed using a LabView-based data acquisition system (see Fig. 2).

3. RESULTS AND DISCUSSION

Figure 3 shows the output power of the laser as a function of neon-only pressure P_{ne} for both natural neon and 50:50 neon between 0.1 to 0.6 mbar. Maximum gain is clearly observed for a pressure of 0.2 mbar of either natural or 50:50 neon isotopic mixture. In the absence of helium, an RF excited neon-only plasma will provide for simultaneous laser oscillation on both lines of the neon doublet split by 51 GHz ($2s_2 \rightarrow 2p_4$ at 1.152276 μm and $2s_4 \rightarrow 2p_7$ at 1.152502 μm) [7]. Due to mode competition, operation on both lines of the neon doublet is useless for gyroscopic operation and it is a key objective of this work to determine the optimal helium to neon gas mixture for rotation sensing.

The optimum helium–neon gas fill was determined by adding a fixed δP_{Ne}, with helium gas incrementally added to the cavity. Over a range of total pressures P_{tot}, we record the laser output power with the discharge driven with 20 W of RF input power. The addition of helium to the gas mix results in a rapid increase in the $2p_7$ population due to cascade from higher-lying states excited by helium. This has the effect of quenching the 1.152502 μm transition [5,7]. As a result, only laser oscillation on the $2s_2 \rightarrow 2p_4$ transition can be observed. Figure 4 illustrates this effect over a range of fixed neon pressures between 0.1 and 0.6 mbar. The effect is most readily observed at lower neon pressures, as the neon-only gain is highest (as shown in Fig. 3). It appears that around 1 mbar of helium is required to entirely quench the 1.152502 μm transition. For helium values at or above this threshold the highest gain can be observed for 0.5 mbar of 50:50 neon for a total gas pressure of around 1.5 mbar.

Ring laser gyroscopes can usefully measure externally imposed rotations within either of two regimes. First, conventional operation on a single longitudinal cavity mode, which is generally achieved in large lasers using gain starvation in an over-pressured cavity. This has the deleterious effect of reduced photon flux incident on the detection system. Alternatively, the tendency for gas lasers to self-phase lock

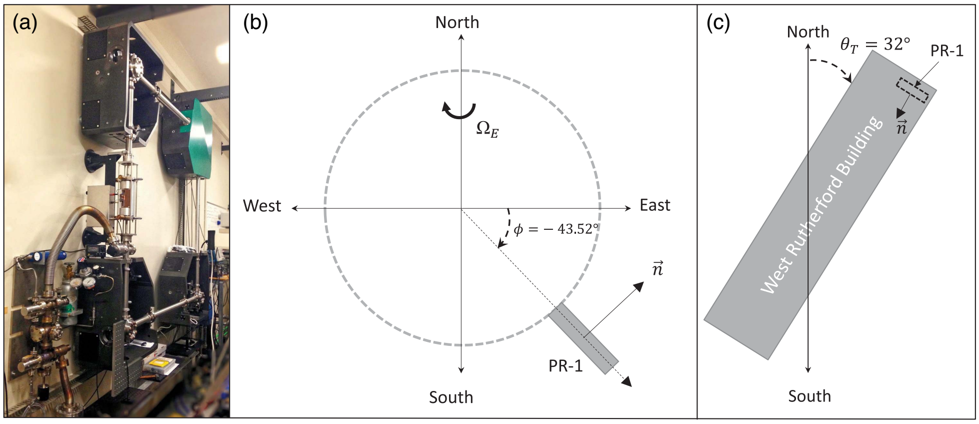

Fig. 1. (a) PR-1 laser system; (b),(c) the geographic orientation of the device with respect to the Earth’s rotation axis.

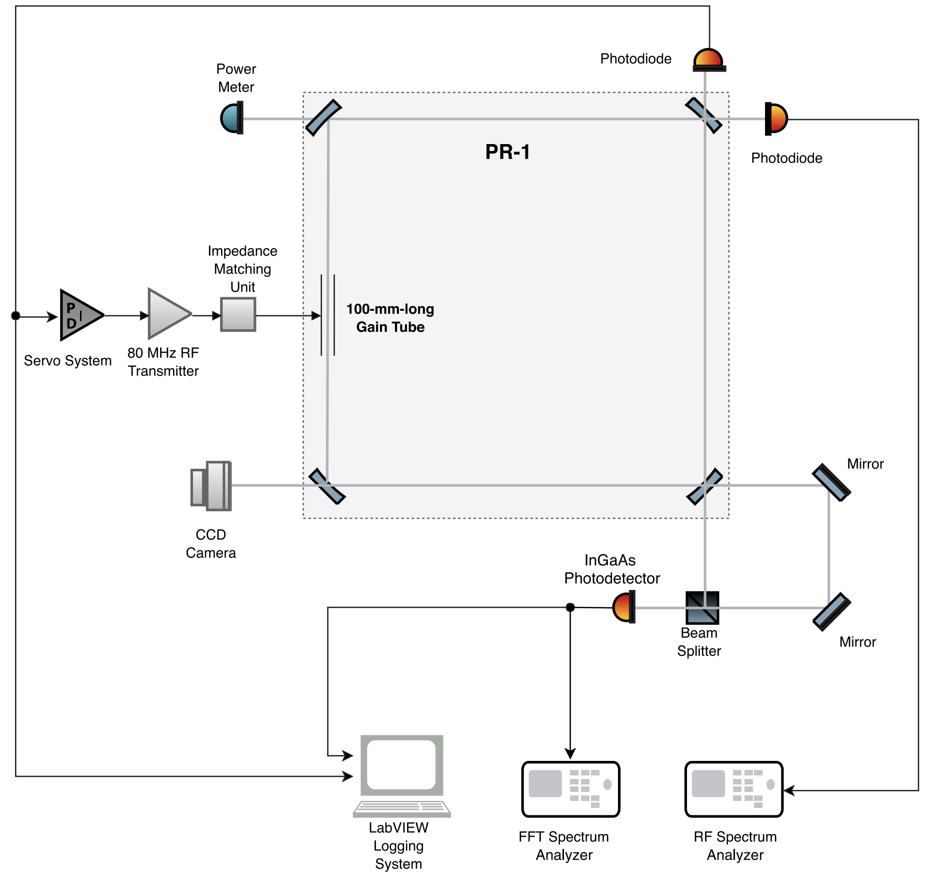

Fig. 2. Schematic of the experimental layout.

on multiple longitudinal modes [8] can be exploited to increase the photon count [9]. We now explore the operational conditions under which the single-mode and phase-locked regimes occur. Figure 5 indicates three distinct regimes of laser output as the excitation density is increased for a given gas mix: (i) the single-mode regime, which we infer from the absence of a beat signal at the free spectral range (FSR) frequency when monitoring the laser output via a fast photodiode connected to an RF spectrum analyzer (together with a stable Sagnac waveform); (ii) a free running multi-mode regime characterized by an FSR beam note and chaotic Sagnac waveform; and (iii) the phase-locked multi-mode regime where an FSR beat note is observable coupled with a stable Sagnac waveform. Note that in both regimes (i) and (iii) a clear Earth line is present on an FFT network analyzer receiving the Sagnac signal. Thus Fig. 5 displays the power thresholds for these three regimes of operation as a function of total gas pressure for fixed quantities of neon between 0.1 and 0.6 mbar. For operation with 0.1 mbar of natural neon, stable rotation sensing can only be achieved in the single-mode regime up to 6 mbar of total gas pressure and no phase-locked regime is measurable. It is notable that for any quantity of neon over the range measured, the multi-mode threshold is quite similar up to 6 mbar of total pressure, typically at values below 10 nW of output power. At higher total pressures the single-mode regime can persist to output powers as high as 58 nW. An additional general observation is that the phase-locked regime tends to be observable only at total pressures above 3–4 mbar and occurs in a series power "bands" as reported earlier [9]. We note here that the purpose of over-pressuring a He–Ne-based ring laser is to induce homogeneous line-broadening, which in turn allows the weak saturation limit to persist at higher powers than it otherwise would, thereby maintaining single-mode operation. It is

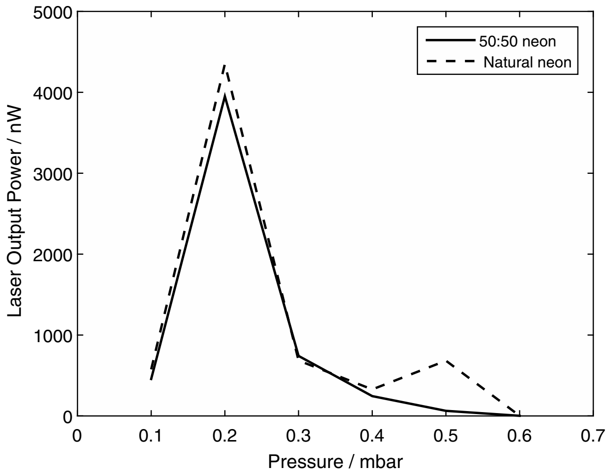

Fig. 3. Laser output power as a function of neon pressure P_{Ne}.

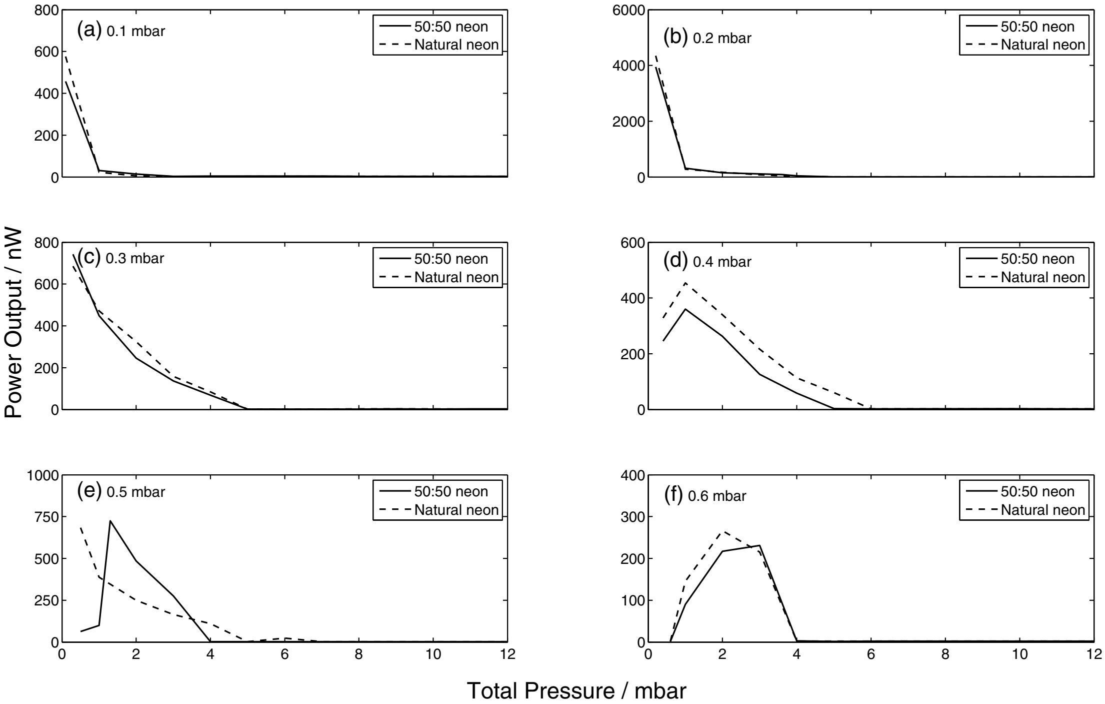

Fig. 4. Measured laser output power at fixed neon partial pressures between 0.1 and 0.6 mbar as a function of total cavity pressure having a constant radio frequency (input) excitation of 20 W.

evident for operation in the infrared that the single-mode regime does not persist to the same power levels as would be observable for operation at a wavelength of 632.8 nm. This can be accounted for by the approximately 4 times smaller homogeneous linewidth of the 1.15 μm transition. Nevertheless, considering both the available gain and the availability of a sufficiently wide power range to maintain single-mode operation, a gas fill of between 0.2 and 0.3 mbar of

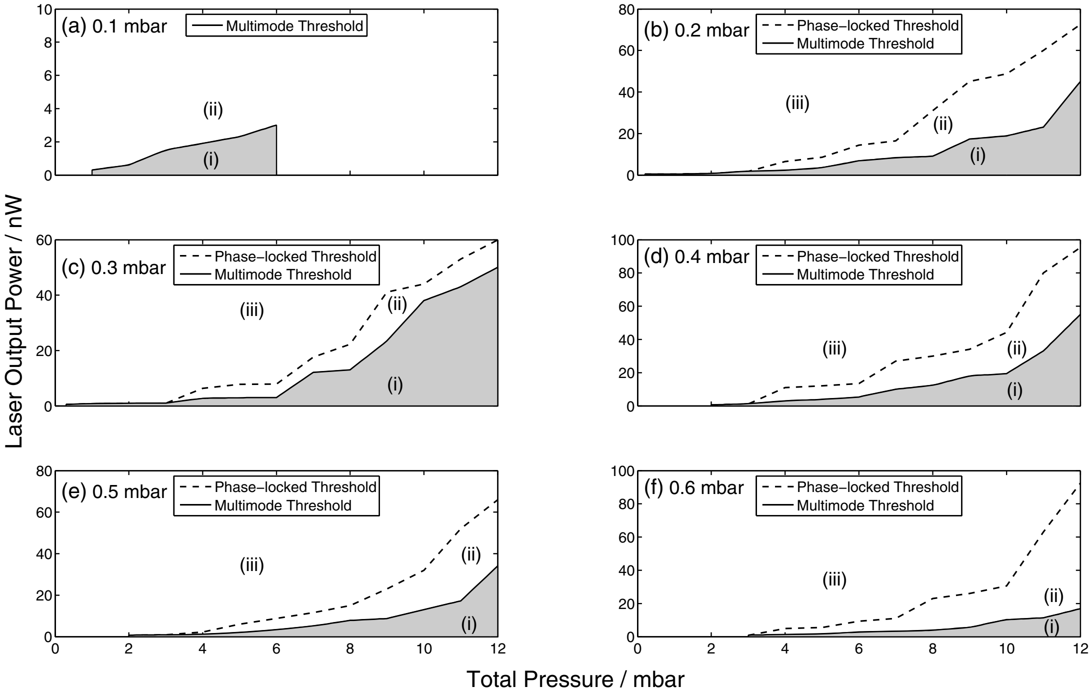

Fig. 5. Measured laser output power at fixed neon partial pressures between 0.1 and 0.6 mbar as a function of total cavity pressure. The shaded area denoted (i) indicates the guaranteed single longitudinal mode operation regime. The area denoted (ii) represents multi-mode operation and that denoted (iii) is a region for which phase-locked multi-mode operation can be attained.

50:50 neon with total pressures above 6 mbar provides the best regime to operate the device as a rotation sensor.

As such, the ring was filled with an optimal mix of 50:50 Ne^{20} and Ne^{22} with 0.2 mbar neon partial pressure (δP_{Ne}) and 6 mbar He–Ne total pressure (P_{tot}). A cold cavity ringdown time τ was measured using a coaxial relay to act as a fast switch to kill the RF excitation. A value of $\tau = 33\ \mu\mathrm{s}$ was measured and this translates into a quality factor of $Q = 2\pi\nu\tau = 5.4 \times 10^{10}$, where ν is the laser operating frequency, 260 THz. The total loss of the cavity, $L = (\tau \times \mathrm{FSR})^{-1}$, is therefore 646 parts per million (ppm) for a FSR of 46.875 MHz. For a direct comparison with ion beam sputtered dielectric mirrors (albeit operating at 632.8 nm for the same gas fill) one obtains $\tau = 135\ \mu s$ and therefore $Q = 4.0 \times 10^{11}$ with $L = 158$ ppm. Note that a significant portion of optical losses in the near-IR crystalline coatings is due to beam clipping given the limited area of the high reflection coating on those mirrors [5].

The Sagnac beat frequency δf measured by a laser gyroscope is given by the equation

$$\delta f = \frac{4A}{\lambda P}\vec{n} \cdot \vec{\Omega}_E, \tag{1}$$

where P is the perimeter (6.4 m), A is the area enclosed by the laser beam, λ is the wavelength of the laser beam, $\vec{n}$ is the normal vector of A, and $\vec{\Omega}_E$ is the angular rotation velocity vector. For the location and orientation of our device (latitude, $\phi = -43.52°$; longitude, $\Phi = 172.58°$) we must account for a tilt $\theta_T = 32°$ east of north. Thus, we re-write Eq. (1) as

$$\delta f = \frac{4A}{\lambda P}\Omega_E \cos\phi \cos\theta_T. \tag{2}$$

Given the Earth rotation rate of $\Omega_E = 7.29 \times 10^{-5}$ rad/s, we anticipate a measured Sagnac frequency of approximately $\delta f = 62.2$ Hz. Figure 6 shows both the inferred relative Allan deviation and the Earth line observed in a power spectrum derived from the Sagnac time series. The measured Sagnac frequency due to Earth rotation is close but observably lower than the expected value, an effect attributable to frequency pulling arising from backscattering effects. As we have discussed previously [5], the sidebands arise from the fundamental rocking mode of the eight-story building in which the laser is located. The Allan deviation presented utilizes gas fills of 0.2 mbar of 50:50 neon with a total pressure of either 2 or 6 mbar. It is readily observable that better results are achieved at higher pressures and this is solely due to the higher photon flux incident on the detection system.

Finally, we remark that we have compared the results obtained here against identical gyroscopic operation using commercially sourced, standard laser mirrors (CVI TLM1 having a BK7 substrate with radius of curvature of 1.5 m) for the same 1.15 μm laser transition. The measured ringdown time for the CVI mirrors is 30 μs yielding a cavity Q of 4.9×10^{10} and indeed, the gyroscope was observed to unlock on the bias provided by Earth rotation alone, yielding a Sagnac frequency which was observed to drift wildly between 50–80 Hz. This is attributable to the fact that the CVI mirrors did not employ a superpolished substrate and therefore the laser was heavily influenced by backscatter-induced frequency pulling—the time variance arising from geometric instabilities associated with the wall-mounted test cavity. However, it does point to the fact that the partial coating of the supermirror substrates (an 8 mm diameter coating on a 25 mm diameter substrate) leads to considerable losses particularly when operating at infrared wavelengths in a large cavity. This is very encouraging since there is a clear path to significantly improved performance. Note that larger crystalline coatings are readily available to reduce the losses induced by beam clipping [10].

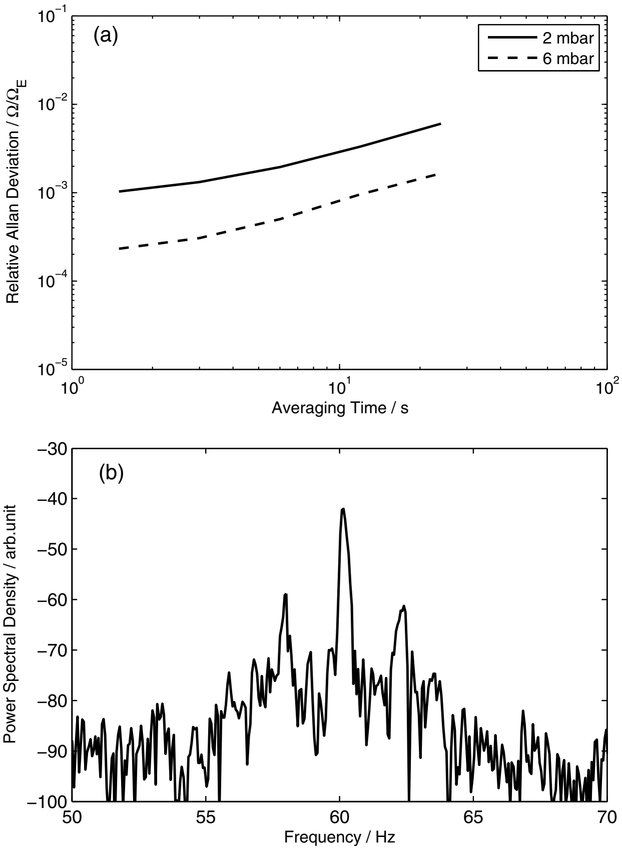

Fig. 6. (a) Relative Allan deviation measured at 0.2 mbar of 50:50 neon with a total pressure of either 2 or 6 mbar, (b) power spectrum of the Sagnac time series showing the Earth line and sidebands due to building motion.

4. CONCLUSION

We have studied, in some detail, a helium–neon-based 6.4 m perimeter laser gyroscope operating on the $2s_2 \rightarrow 2p_4$ transition of neon at a wavelength of 1.152276 μm. Our cavity is constructed from GaAs/AlGaAs crystalline coated, fused silica supermirrors in contrast to the commonly employed ion beam sputtered mirrors. As constructed, the laser readily unlocks on Earth rotation having a Sagnac beat note at close to 60 Hz. The estimated lock threshold at approximately 3% of the projected Earth rotation rate as inferred from the magnitude of backscattering effects [5], which are comparable with those observed for operation at 632.8 nm. A ringdown time of $\tau = 33\ \mu\mathrm{s}$ was measured, yielding a $Q = 2\pi\nu\tau = 5.4 \times 10^{10}$. We find that the optimum gas composition for gyroscopic operation is

0.2 and 0.3 mbar of 50:50 neon with total pressures above 6 mbar. It appears that the biggest performance limitation is currently the partial coating of the mirror substrate, which leads to additional loss by transmission around the coating edges.

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