Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2018-389-AC2, 2019

Atmospheric Measurement Techniques
Discussions
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AMTD

Interactive comment

Interactive comment on "Laser frequency stabilization based on an universal sub-Doppler NICE-OHMS instrumentation for the potential application in atmospheric Lidar" *by* Y. Zhou et al.

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Received and published: 26 January 2019

The answers to the reviewers' comments are as follows, the revised paper is added to the Supplement.

This paper develops a NICE-OHMS-based laser stabilisation system for potential application for lidar. The authors provide a brief overview of the relevant technical aspects of the paper, including sub-Doppler spectroscopy, the NICE-OHMS technique and the laser technology used in various NICE-OHMS demonstrations. The highlight of the paper is the application and use of a fiber-coupled optical single-sideband electooptic modulator (f-SSM) to make the system useful for laser stabilisation to a variety

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Discussion paper

of lasers, and they demonstrated this by stabilising both an Erbium-doped fiber laser (EDFL) and a whispering gallery mode (WGM) laser. After producing a sD NICEC1 OHMS signal with each laser (using acetylene as a reference gas), each laser was then stabilised to that acetylene transition frequency using the sD NICE-OHMS signal produced. The stability of the stabilised output was measured and found to exceed the level needed for use in lidar systems. The paper is well organised and clearly written, for the most part. Although the applicability of this system to lidar needs to be expanded upon, I see no reason why it could not be used as a stabilised seed laser for lidar.

Answer: Thanks for your positive comments.

Specific comments: What was the acetylene gas source for your initial experimental realization of this, and how did you measure that it was at 100mTorr? Do you know the long-term stability of the pressure in the system? Would you expect to use the same system setup "in the field" when supporting a Lidar system?

Answer: Thanks for the comments. "total pressure and 1000 ppm concentration" and "The pressure leaking rate for the cavity was smaller than 0.01 mTorr/min after it was closed by the vacuum valve (Leycon 215379, Oerlikon, Germany)." are inserted into the first paragraph of section 3. The sub-Doppler NICE-OHMS setup should be integrated and miniaturized before it is applied to the Lidar system. In this status, it can not be applied to the Lidar system.

Can you be more explicit about the stability requirements of a lidar system? What about the power required to stabilize such a system, can you give the details of the power requirement and can your system provide that power?

Answer: Thanks for the comments. "In reality, the required frequency stability is ranging from hundreds of kHz to dozens of MHz, which relies on the linewidth of the target gas spectrum [1]." and "Therefore, the Jet Propulsion Laboratory in USA has designed a frequency stabilization system for coherent Lidar application with frequency error of 2.06 MHz for detection of $\nu 1+\nu 3$ band of acetylene [2]; The group in University of Maryland has designed another frequency stabilization system with frequency drift better than 0.3 MHz for the detection of CO2 at the wavelength of 1572 nm [3]." are insert to the first paragraph of section 1.

Lidar systems also would like to target other molecules, especially those related to greenhouse gas emissions (CO2, methane, etc.) Can you comment on how adaptable your system is to these other molecular species?

Answer: hanks for the comments. "However if this setup is applied to the detection of CO2, CH4 or other gases, the saturation power of the target molecular transition, as a function of dipole moment, laser beam waist and total pressure, should be determined firstly to choose a suitable laser and a proper cavity design. The transition dipole moment is the function of its linestrength, life time and partition function (Ma et al., 2008). Normally, for a weak absorption line with the saturation power in the order of hundreds of watts, a cavity with finesse of more than tens thousands and a laser with its linewidth of the order of kHz are required." is added to the last paragraph of section 5. The saturation powers for the target two transitions are also added in the proper positions in section 3.

Can you provide any comments at the end of your paper to indicate what changes would need to be made to your system for it to work reliably outside a research laboratory, "in the field"? Answer: Thanks for the comments. "Although the frequency stability can satisfy the requirements of a real Lidar system, the whole setup should be miniaturized and a seismic design is necessary before it is applied to the real field." is insert into the last paragraph of section 5.

Page 3: Line 1: I am confused by this first sentence. The "noise immunity" obviously refers to "noise" sources - not the actual signal. The "background signal" you mention is induced by other processes unrelated to the "noise" in the "noise immunity" – from optical power variations in the incident light to the cavity, or coupling efficiency. Can you please clarify or remove this sentence?

Answer: Thanks for the comments. The noise in “noise immunity” refers solely to the frequency to amplitude noise. The influence of this noise to the NICE-OHMS signal (i.e. the demodulated cavity enhanced frequency modulation signal) is null only under the condition of empty cavity, zero residual amplitude modulation from EOM and other background noise before the cavity. If the laser addresses the molecular transition, the absorption will make the cavity transmitted triplet different noise level and therefore destroy the noise immunity property to some extend. We remove “often referred to as a background signal” from the line in the text.

Page 6: Line 6: “for integration times up to 240 sec” - I might argue that you have overestimated your white noise response window, especially in the case of the fiber laser Allan deviation data (black points and curve). I would estimate (reading directly off Figure 4) that there is a white noise response out to 100-120 seconds (the intersection of your “white noise” line and a flat line indicating the ADEV value when the ADEV begins drifting up), rather than 240 seconds, for the fiber laser. By 240 seconds you are clearly out of the white noise regime. However, it is a bit difficult to see this clearly from the graph. Additionally, it is not obvious that there are any “dotted” lines on this plot, as mentioned in the figure caption - the “white noise response” lines appear solid. Figure 3: To be able to better compare the signal-to-noise-ratio of the sD NICE-OHMS signals in sub-plots (a) and (b), it would be helpful to have the y-axes have the same minimum and maximum values (perhaps 0.7 or 0.65).

Answer: Thanks for your reminding. The corresponding changes have done in the revised version.

Technical corrections: Page 1: Line 1: Typically one would use “a universal” rather than “an universal”. Line 26: “a relative weak” -> a relatively weak; Page 2: Line 22: “cavity with a finesse of 105” - > “cavity with a finesse of 100,000” or “cavity with a finesse of 10ËĘ5” Line 24: should be rewritten - “sensitivity of 1x10ËĘ-14 cm-1 at 1-s averaging time." Page 3: Line 6/7: "more than one frequency actuators are usually utilized often a" ->"more than one frequency actuator is usually utilized, often a" Page 5: Line 30: "The performance of the this frequency stabilization were assessed by" -> "The performance of the this frequency stabilization were was assessed by" Page 6: Line 15: "testified" - > "tested"

Answer: The corrections are done in the revised version.

Generally there is sometimes an issue of spacing between text and the beginning or end of parentheses that should be checked for throughout the paper.

Answer: The corrections are done in the revised version.

It is a bit confusing to have two very similar References (Ehlers, 2014) and (Ehlers et al., 2014) in the paper text, there a way to differentiate? (Ehlers [Thesis], 2014)? Also, I am not sure that the page 7, line 24 Ehlers reference, is correct. Perhaps use "PhD dissertation" rather than "Doctor". "Ehlers, P.: Further development of NICE-OHMS – an ultra-sensitive frequency-modulated cavity-enhanced laser-based spectroscopic technique for detection of molecules in gas phase, PhD dissertation, Umeå universitet, Umeå, 2014."

Answer: The corrections for all the references are done in the revised version.

New added references

1. G. Ehret, C. Kiemle, M. Wirth, A. Amediek, A. Fix, and S. Houweling, "Space-borne remote sensing of CO2, CH4, and N2O by integrated path differential absorption lidar: a sensitivity analysis," Appl. Phys. B. 90, 593-608 (2008).

2. P. J. Meras, I. Y. Poberezhskiy, D. H. Chang, J. Levin, and G. D. Spiers, "Laser frequency stabilization for coherent lidar applications using novel all-fiber gas reference cell fabrication technique," in 24th International Laser Radar Conference, (Boulder, Colorado, 2008).

3. K. Numata, J. R. Chen, S. T. Wu, J. B. Abshire, and M. A. Krainak, "Frequency stabilization of distributed-feedback laser diodes at 1572 nm for lidar measurements of atmospheric carbon dioxide," Appl. Optics. 50, 1047-1056 (2011).

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2018-389/amt-2018-389-AC2-supplement.pdf

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Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2018-389, 2018.