

Review of Further Advancement in Pound-Drever-Hall (PDH) Technology Development

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Abstract: Due to instability caused by uncontrollable factors such as temperature change and minor vibrations, as well as line broadening, traditional laser devices often fail to produce a steady output suitable for high-precision applications. Now Pound-Drever-Hall (PDH) technology can help take a shortcut in this area. This research focuses on previously published studies that modify PDH technology, primarily aimed at enhancing the range or precision of laser stabilization, while also gathering insights from further research in this field. Concentrating on the main progress for the advancement in PDH technology, this research use data and paper available to conclude, compare, and integrate so that more advanced researches can have better usage for improvement and application. Particularly, most cases each now is still looking for a specific point that can further improve the technique to make the output more stable and as accurate as expected. But if those specific points are combined in the future, the adaptability and practicality can be largely improved, there can be lasers fit to current needs for high-precision stable laser instrument which is able to keep working for quite a long time.

Keywords: Lasers, Laser stabilization, Phase modulation, Electro optics, PDH technology

1. Introduction

Lasers often lack the stability required for advanced research and production needs due to factors such as temperature increases during operation and disturbances from both artificial and natural sources, which significantly affect the output laser frequency. Numerous studies have explored solutions to this issue, with PDH technology emerging as the most popular approach due to its universal applicability. Many researchers are now digging deeper into this technique. So this research is intended to gather some of the important studies and glean different methods in further improving the PDH technology, in the wake of which provide possible future research direction in this field. Nowadays most researches dig into a very specific aspect of PDH technology, like using double modulation to work in two ranges to cooperate, using one but modulating at multiple phases to get more detailed information, as well as replacing some of the component of the device including using Fano resonance instead of F-P cavity, which provide practical and promising visions for pioneer laser devices[1-3]. This effort represents a meaningful step toward consolidating existing resources, facilitating comparisons, and examining potential connections between various studies. Given the scarcity of comprehensive research on this subject, reviewing these independent studies is essential to gather the necessary information and develop new advancements based on

previous findings. Further researches upon this are likely to absorb the advantages of previous researches so that the PDH technology can be more suitable for practical high-standard applications, and enterprises and research institutes can use this for better detection and industrial processing.

2. Basis of PDH technology

2.1. Principle

The PDH technology generally uses a real-time feedback system to test whether the output laser frequency is up to the standard, and generates an error signal to adjust the laser cavity. As shown in Fig 1, after being emitted by the laser, the light will pass an electrical optical modulator (EOM) to have phase modulation. Then it goes through a polarization beam splitter (PBS), becomes polarized, and enters the optical cavity, such as an F-P cavity. It will finally come out and be polarized again so that it goes another way in the PBS. The detector collects this light and it will be demodulated at the same frequency to make an error signal, which is filtered by the low-pass filter and at last it is sent to a controller to physically change the feature of the laser cavity, forming a negative feedback system to improve its stability. The error signal expression is as follows:

$$E \approx -\frac{4}{\pi} \sqrt{P_c P_s} \frac{\Delta\omega}{\Delta\nu} \quad (1)$$

$\Delta\omega$ is the frequency change; $\Delta\nu$ is the full width at half maximum of the F-P cavity; P_c is the carrier power; P_s is the sideband power

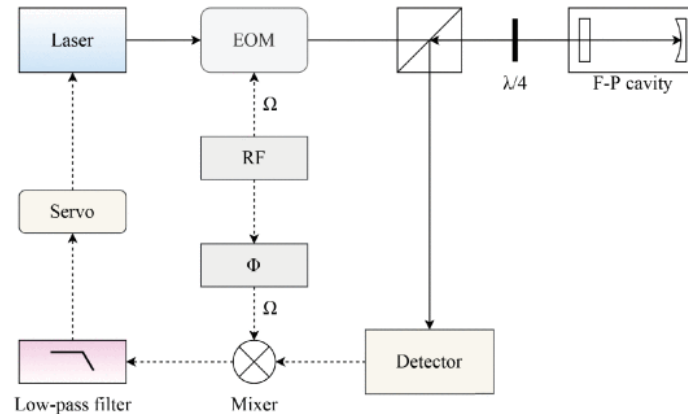


Figure 1: PDH technology principle[4]

The effect of this technique is obvious and inspiring. An experiment testing the effects of PDH technology on the SA200-5B type F-P cavity (1.5 GHz) demonstrates that, within 10 seconds before and after locking, there is a substantial difference. As shown in Fig 2, when operating freely, the frequency fluctuation is around 3.5MHz, and after frequency locking, it is within 600 kHz.

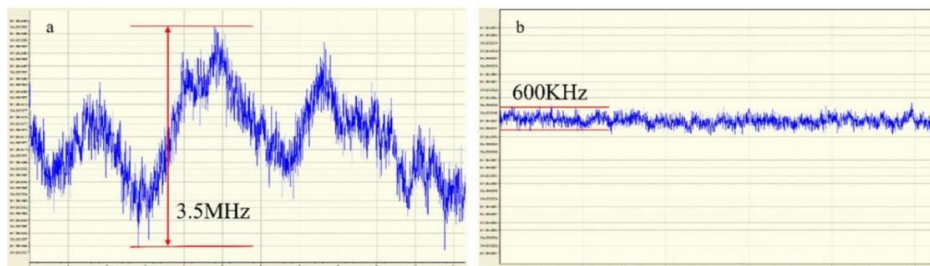


Figure 2: Comparison in using PDH or not[5]

2.2. Enhancement

Several advancements have been made by integrating related techniques in optics to improve the efficiency of PDH technology. Coherent PDH technology combines coherent detection into PDH technology which can be fit for the interrogation of fiber sensor arrays and sensing low-power signal. The frequency components involved in the process of PDH are transferred from the former optical domain into the radio frequency domain. The power for detection is obviously lower (15 dB than the previous one), providing greater potential for various applications [4].

Simultaneously, active PDH technology mixes the injection locking technology to enhance the precision of the sensors and improve the signal-to-noise ratio. It puts the weak standard signal into the cavity to act with oscillator, so that the laser can be stabilized from the source.

3. Deeper PDH technology

3.1. Special PDH technology

Now the PDH technology is not limited to the original principle in many ways. Basically, for example, there is an experiment on using an acousto-optic modulator (AOM) instead of former electric-optic ones applied in the system of PDH technology. For the phase modulation in this technique, when using an electric-optic modulator, all the effects on the light such as slight polarization and the sideband of the light can lead to wrong analysis after demodulation. This new approach basically uses an AOM operating in the Bragg diffraction regime (AOM-B) as an external phase modulator. The AOM-B driver in the specific experiment consists of a signal generator, an attenuator, and a power amplifier. It not only does phase modulation but also adjusts the light amplitude [6]. The laser here is a diode laser (New FocusVortex 6000, Newport Corp), and a satisfying result is shown in Fig 3.

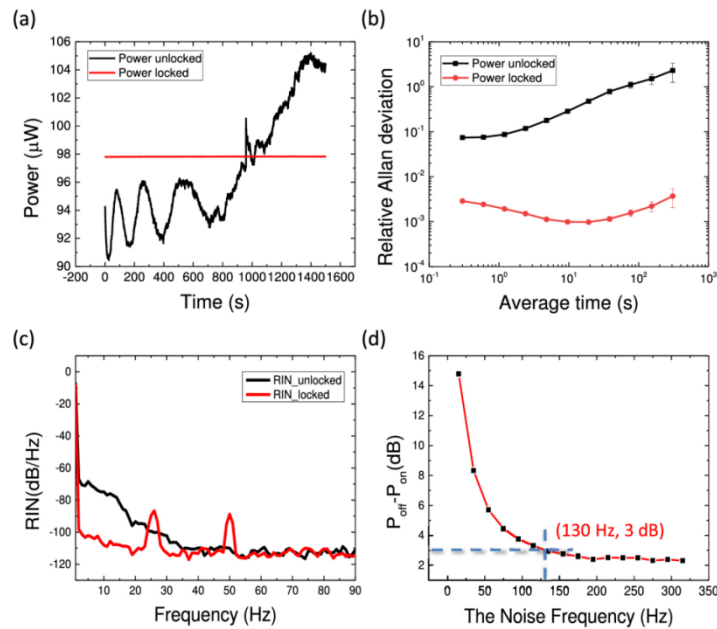


Figure 3: Power stabilization of the cavity coupling light (a) Detected power in front of the cavity. Black line: power unlocked, red line: power locked. (b) Corresponding relative Allan deviations of the measured power. (c) Relative intensity noise signals. (d) Relative power difference at the introduced noise frequency when the servo is on/off[6]

This method contrasts with another approach demonstrated by Baryshev, which uses a different acousto-optic modulator operating in the Raman-Nath diffraction regime. Unlike the previous technique, this system is less affected by environmental factors like temperature and electrical noise. Also, it is insensitive to light polarization and produces only a single sideband, significantly improving the precision of the error signal by reducing noise.

There are also methods that involve selecting or modifying the optical cavity to achieve different models. Research has shown that microcavities, particularly microcylinder cavities, exhibit relatively low noise caused by thermal motion, approaching the error signal quality of well-established PDH technology[3][7]. This technique is more complicated because it uses Fano resonance, but it also benefits from its complexity to some extent. The so-called whispering gallery mode(WGM) can provide a precise locking source, but still can generate noise from heat, affecting the system a lot because of its small size. This research, however, identifies a connection between disturbances in various models and resonance frequencies, thus comparing this to the error signal as the traditional PDH technology to adjust the cavity with much more precision[3].

3.2. Two depths modulation

While researchers explore different models in PDH technology, there have also been advancements aimed at enhancing the feedback system's foundation. The traditional PDH technology usually faces the disadvantage of a narrow linear dynamic range and susceptibility to interference. So here comes an adaptive stabilization method based on two modulation depths shown in Fig 4.

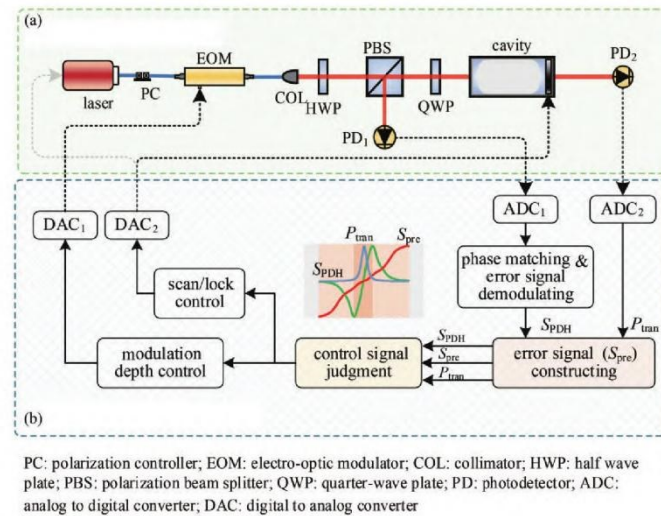


Figure 4: PDH locking method based on double modulation depths[1]

This method allows for two relatively independent feedback loops to operate within a single laser system. The system retains the traditional feedback approach, but it collects light from both the front and back of the cavity into two detectors with distinct detection ranges. Simply, the one with the larger range (S_{pre}) is for pre-locking, used for putting the frequency to the range of the more precise one (S_{PDH}). Then, the precise locking works, making it better than the traditional one. Due to this design, the system reaches both precision and adaptive, along with a quick switch in both models(<30 μ s), which can realize long-term high-quality locking[1].

5. Conclusion

This research briefly discusses the PDH technology as well as those enhancements and improvements done by different kinds of researches like enriching error signal or changing cavity. Several weaknesses in the technology have been identified and addressed, though this discussion does not encompass all the progress made in this field. Many developments remain unsatisfactory for researchers, as they lack comprehensive and complete solutions. While PDH technology holds great promise and can be applied broadly, much more exploration is required. However, without delving into the theoretical derivations of these studies, this paper can only offer methodological insights rather than substantive improvements. The focus here is on methods already in use. Further theoretical analysis could reveal greater commonalities among these approaches, leading to more effective advancements.

References

- [1] Yan Liping, Zhang Zhewei, Xie Jiandong, Lou Yingtian & Chen Benyong. (2023). Adaptive PDH Frequency Stabilization Method with Large Linear Dynamic Range Based on Two Modulation Depths. *Acta Optica Sinica*(19), 123-134.
- [2] Su Juan, Jiao Mingxing, Jiang Fei, Xing Junhong. Research on Laser Frequency Stabilization Techniques Using Orthogonally Demodulated Pound-Drever-Hall Method[J]. *Laser & Optoelectronics Progress*, 2018, 55(8): 081404.
- [3] Yaohui Xu, Haotian Wang, Jun Guo, Jianing Zhang, Wei Zhou, and Deyuan Shen, "Laser frequency stabilization based on Fano resonance in a microcylinder cavity," *Opt. Lett.* 48, 4288-4291 (2023)
- [4] X. Zhan, Z. Wang, S. Kumar, C. Marques, X. Li and R. Min, "The Application of Pound–Drever–Hall Technology in High-Resolution Sensing—A Review," in *IEEE Sensors Journal*, vol. 23, no. 7, pp. 6427-6438, 1 April 2023, doi: 10.1109/JSEN.2023.3244941.
- [5] Wang Xinlong, Gao Jun, Ye Hanli and Wang Chensheng. Research on Laser frequency stabilization with PDH technique based on F-P cavity. *Laser Technology* 1-10.
- [6] Yong Zeng, Zhuo Fu, Yang-Yang Liu, Xiao-Dong He, Min Liu, Peng Xu, Xiao-Hong Sun, and Jin Wang, "Stabilizing a laser frequency by the Pound–Drever–Hall technique with an acousto-optic modulator," *Appl. Opt.* 60, 1159-1163 (2021).
- [7] WANG Meng-yu ,JIN Xue-ying ,WANG Jing ,CHEN Li-ming ,WANG Ke-yi. (2017). Analysis of the Pound-Drever-Hall Frequency Stabilization Technique Based on a Whispering Gallery Mode Optical Microsphere Cavity. *ACTA PHOTONICA SINICA* (07), 61-68.
- [8] Xiaojun Jin, Yi Lin, Ying Lu, Huilian Ma, and Zhonghe Jin, "Short fiber resonant optic gyroscope using the high-frequency Pound–Drever–Hall technique," *Appl. Opt.* 57, 5789-5793 (2018).
- [9] Manuel Zeyen, Lukas Affolter, Marwan Abdou Ahmed, Thomas Graf, Oguzhan Kara, Klaus Kirch, Adrian Langenbach, Mirosław Marszałek, François Nez, Ahmed Ouf, Randolph Pohl, Siddharth Rajamohanan, Pauline Yzombard, Karsten Schuhmann, and Aldo Antognini, "Injection-seeded high-power Yb:YAG thin-disk laser stabilized by the Pound-Drever-Hall method," *Opt. Express* 31, 29558-29572 (2023).
- [10] Zhou Xian, Feng Liwen, Zhuang Dehao, et al. RF resonant ring locking using Pound-Drever-Hall technique[J]. *High Power Laser and Particle Beams*, 2018, 30: 123002.