Optics Letters

Control of the VCSEL spectrum by dual microwave frequency modulation

Alexander P. Bogatov,[1] Alexander E. Drakin,[1] Maria I. Vaskovskaya,[1] Dmitry S. Chuchelov,[1] Kirill M. Sabakar,[1] Eugene A. Tsygankov,[1,*] Vitaly V. Vassiliev,[1] Vladimir L. Velichansky,[1,2] and Sergey A. Zibrov[1]

[1]Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, 119991, Russia
[2]National Research Nuclear University MEPhI, Kashirskoye Highway 31, Moscow, 115409, Russia
*Corresponding author: selentinthebright@gmail.com

Received 29 September 2022; revised 8 November 2022; accepted 10 November 2022; posted 10 November 2022; published 12 December 2022

We propose and investigate a method for controlling the spectrum of the vertical-cavity surface-emitting laser by simultaneous modulation of the injection current at single and doubled frequencies. We experimentally demonstrate the ability to control the power asymmetry of the first-order sidebands and to suppress the carrier by the proposed method. These possibilities are beneficial to improve frequency stability of atomic clocks based on the effect of coherent population trapping.

https://doi.org/10.1364/OL.476838

Efficient microwave modulation of vertical-cavity surface-emitting lasers (VCSEL) is used in many applications [1]. One of them is detection of the coherent population trapping (CPT) resonance in compact atomic clocks [2], since modulation of the laser injection current provides spectral components with correlated phases. In this application, particularly important is the following property of small-aperture (<5 μm) polarization-maintaining VCSELs. They retain a single-mode operation under deep microwave current modulation (more than five distinct spectral components). Thus, the spectrum is polychromatic but the laser generation occurs in the fundamental transverse mode and a single longitudinal mode (there are no others within the gain width). This is an important advantage over edge emitting lasers since the presence of other longitudinal modes decreases the CPT resonance contrast and leads to the mode-partition noise.

However, the single-mode operation is not the only condition for high frequency stability of CPT-based clocks. There are additional stringent requirements for the polychromatic spectrum of a laser. Here, we consider the typical version of CPT-based clocks where the current modulation frequency is equal to one half of the hyperfine splitting of an alkali-metal ground state. The first two sidebands that are tuned to resonant absorption lines should have optimal and equal intensities to provide a maximal signal-to-noise ratio. The light shift of the CPT resonance frequency should be suppressed to reduce deterioration of the frequency stability. It can be done by adjusting the laser spectrum (via change of the microwave power) since the carrier and the first two sidebands increase the CPT resonance frequency while the higher-order sidebands decrease it [3–7].

One of the distinctive features of the VCSEL spectrum under microwave current modulation is its asymmetry. In most cases, the powers of the sidebands equidistant from the carrier are unequal. The phenomenological explanation of this feature is that the laser field has properties of both frequency and amplitude modulation. Indeed, a large number of spectral components is typical for frequency modulation, while the presence of amplitude modulation can provide a spectrum asymmetry. However, the VCSEL spectra of various companies that we have studied (ULM Photonics, Vixar, Thorlabs) have a different type of asymmetry than that of the optical field undergoing phase-amplitude modulation [8]. Another distinctive feature is that powers of spectral components do not reach a zero level, while this is always the case for a phase modulated field.

We explained the features of VCSELs spectra within the framework of a developed self-consistent theory based on Maxwell's equations that accounts for the interaction of spectral components in the laser active medium. In this way, we derived analytical solutions for cases where there are only three or five dominating components in the laser spectra [8,9]. The obtained solutions correctly describe the occurrence of a maximum in the dependencies of modulation efficiency and the power ratio of the second sidebands on amplitude of current modulation. To describe spectra with a greater number of components which appear under deep current modulation, we derived a numerical solution [10]. The developed theory demonstrated the correct type of spectrum asymmetry and predicted the possibility of controlling the VCSEL spectrum by simultaneous modulation of the injection current at single (Ω) and doubled (2Ω) frequencies: $J(t) = J_0 + J_1 \cos \Omega t + J_2 \cos(2\Omega t + \varphi)$. The proposed technique gives two additional parameters that can be varied in order to manipulate the spectrum. They are the ratio of the amplitudes of two current modulations, J_2/J_1, and the phase shift between them, φ. Conventionally, there are only two parameters that govern the characteristics of VCSEL radiation, that is the temperature of the active region and the injection

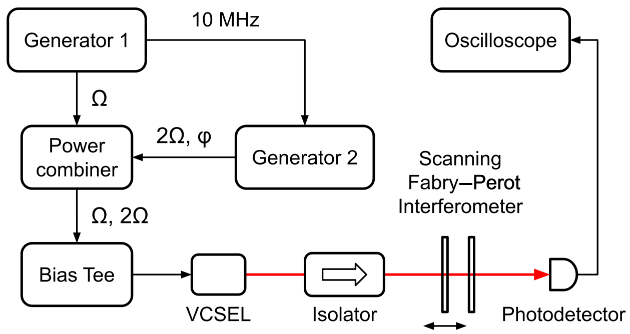

Fig. 1. Scheme of the experimental setup.

current. They are not independent since their combination determines wavelength, which has to be tuned to resonant atomic line.

In this Letter, we experimentally demonstrate complete carrier suppression and the ability to control the power asymmetry of the first-order sidebands using the proposed method. We remember here that the carrier power reaches a minimum, but non-zero value at a certain modulation amplitude if only one frequency is used. The optical part of the experimental setup (Fig. 1) consists of a VCSEL (ULM Photonics), an optical isolator, a scanning Fabry–Perot interferometer, and a photodetector. The laser threshold current is 0.55 mA and the temperature is maintained at 25°C. Two microwave generators, Agilent E4428C (Generator 1) and Agilent E8257D (Generator 2) are used for RF current modulation at 3 GHz and 6 GHz frequencies, respectively. Both signals are mixed by a Mini-circuits ZFRSC-183-S+ power combiner and fed to the laser via Mini-circuits ZFBT-6GW-FT+ bias tee. The internal crystal oscillators of the generators are phase-locked using a 10 MHz signal. The phase shift φ between two microwave signals is fine-tuned using the built-in function of the generator providing modulation at doubled frequency.

The laser spectra (Fig. 2) are obtained at the laser injection current equal to 1.33 mA, which is close to the maximal modulation efficiency at 3 GHz frequency [9]. Figure 2(a) shows that the laser spectrum under modulation at a frequency of 3 GHz has a strong asymmetry, which is typical for VCSELs. The additional low-depth modulation at 6 GHz [Fig. 2(b)] results in a drastic change in spectral power distribution. We found that the carrier power can be decreased down to the noise level while the difference in the first sidebands powers can be made to be less than 1% [Fig. 2(c)]. The value of the phase shift between two microwave signals for this case is denoted as φ_0. The carrier suppression and small difference of the first sidebands ratio are quite robust to parameters of the additional current modulation. To keep the carrier power less than 10^{-2} of the sum of the first sidebands powers the tolerances of the phase shift and the single-frequency microwave power are $\varphi_0 \pm 10°$ and $P_1 \pm 5\%$, respectively. Variations of the double-frequency microwave power, P_2, have a much smaller effect on the carrier amplitude because the modulation efficiency is quite low for the chosen value of the injection current. Moreover, spectra with the indicated features are observed in the injection current range of 1.27–1.37 mA. For these currents the correct values of P_1, P_2, and φ can be found. The corresponding spectra differ in the power distribution between the sidebands. Similar results are observed with VCSELs manufactured by VIXAR company.

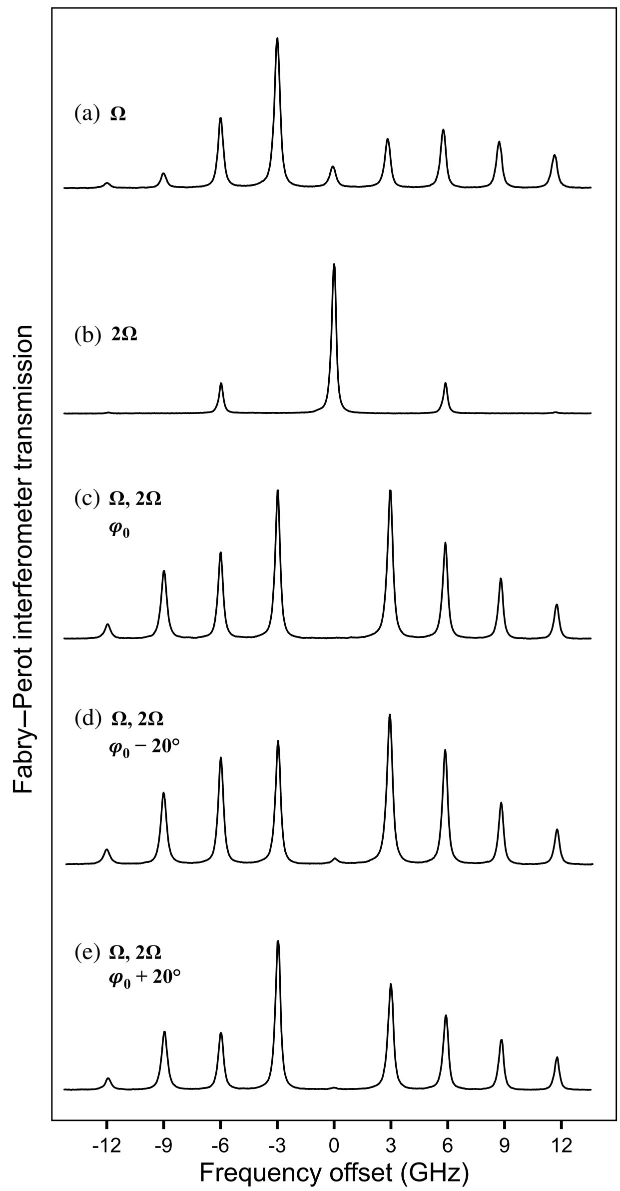

Fig. 2. Spectra of an ULM Photonics VCSEL generating at 795 nm. The injection current is modulated at (a) 3 GHz, (b) 6 GHz, (c)–(e) 3 GHz and 6 GHz with phase shift φ equal to φ_0, $\varphi_0 - 20°$, and $\varphi_0 + 20°$, respectively. The power of the maximum component is set equal to 1 for each spectrum. The powers of microwave signals are −7.7 dBm for 3 GHz and 12.5 dBm for 6 GHz.

Typical optical and electric characteristics of the investigated lasers can be found in Ref. [8].

Thus, the proposed technique gives a possibility to simultaneously equalize the powers of the two first sidebands and to suppress the carrier. Both of these spectrum features can improve the frequency stability of CPT-based clocks. The particularly negative effect of the carrier on stability stems from the following. The carrier induces the largest light shift (normalized to intensity) among non-resonant spectral components since its frequency detuning from atomic transitions is minimal and both energy-level shifts increase the CPT resonance frequency. In contrast, the light shifts produced by the sidebands of higher order are determined by the difference of the relevant energy-level shifts. Therefore, the high-order sidebands should contain a higher amount of optical power for suppression of the total light shift. In the general case, this leads to a greater concentration of optical power in non-resonant spectral components, which reduces the CPT resonance contrast and short-term frequency stability. It is also important to note that for a phase-modulated optical field the theory predicts zero light shift when the carrier power is nullified at a modulation index (ratio of the frequency deviation to the modulation frequency) close to 2.405 [11]. A significant optical line broadening leads to a change in the modulation index, at which the light shift is zero [12]. However, for a VCSEL under deep current modulation, the zero carrier power does not guarantee elimination of the light shift.

The detrimental effect of a difference in powers of the first-order sidebands is the following. Firstly, the CPT resonance contrast reaches a maximum when intensities of the resonant sidebands are equal (at their fixed total power) [13]. Therefore, power equalization is beneficial for short-term frequency stability. Secondly, spectrum asymmetry is one of the sources leading to the intensity nonlinearity of the CPT resonance frequency [14]. As a consequence, techniques for suppression of the light shift based on a modulation of the optical field intensity (see, for example, Ref. [15]) provide spectrum which still shifts the metrological transition frequency. The shift value depends on the laser field parameters and, in the general case, it can undergo long-term drift, deteriorating the frequency stability. Thus, symmetrization of the laser spectrum can decrease a nonlinear dependence of the CPT resonance frequency on optical field intensity and make techniques controlling the spectrum by modulating the laser field intensity more robust. We also note that the carrier suppression leads to the absence of contributions to the CPT resonance from it and the second-order sidebands, which can reduce asymmetry of the resonance to an even greater extent.

To summarize, we confirmed the possibility of suppressing the carrier power in the spectrum of modulated VCSEL with the help of additional current modulation at doubled frequency which was predicted by theory developed for deep current modulation. In addition, we showed that this suppression can be achieved at very close powers of the first sidebands. We expect that application of this technique to CPT-based clocks can improve their frequency stability.

Funding. Russian Science Foundation (19-12-00417).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES

1. R. Michalzik, *VCSELs: Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers* (Springer Berlin Heidelberg, 2012).
2. V. Shah and J. Kitching, *Advances in Atomic, Molecular, and Optical Physics* (Academic Press, 2010), pp. 21–74.
3. F. Levi, A. Godone, and J. Vanier, IEEE Trans. Ultrason., Ferroelect., Freq. Contr. **47**, 466 (2000).
4. M. Zhu and L. S. Cutler, in *Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Meeting*, (United States Naval Observatory, 2000), pp. 311–324.
5. R. Lutwak, D. Emmons, W. Riley, and R. M. Garvey, in *Proceedings of the 34nd Annual Precise Time and Time Interval (PTTI) Meeting*, (United States Naval Observatory, 2002), pp. 539–550.
6. C. Affolderbach, C. Andreeva, S. Cartaleva, T. Karaulanov, G. Mileti, and D. Slavov, Appl. Phys. B **80**, 841 (2005).
7. R. Boudot, P. Dziuban, M. Hasegawa, R. K. Chutani, S. Galliou, V. Giordano, and C. Gorecki, J. Appl. Phys. **109**, 014912 (2011).
8. E. A. Tsygankov, S. A. Zibrov, M. I. Vaskovskaya, D. S. Chuchelov, V. V. Vassiliev, V. L. Velichansky, A. E. Drakin, and A. P. Bogatov, Opt. Express **30**, 2748 (2022).
9. M. I. Vas'kovskaya, V. V. Vassilev, S. A. Zibrov, V. L. Velichansky, I. V. Akimova, A. P. Bogatov, and A. E. Drakin, Quantum Electron. **47**, 835 (2017).
10. E. A. Tsygankov, S. A. Zibrov, M. I. Vaskovskaya, D. S. Chuchelov, V. V. Vassiliev, V. L. Velichansky, A. E. Drakin, and A. P. Bogatov, are preparing a manuscript to be called "Self-consistent approach for calculation of VCSEL spectra under deep microwave current modulation".
11. D. S. Chuchelov, V. V. Vassiliev, M. I. Vaskovskaya, V. L. Velichansky, E. A. Tsygankov, S. A. Zibrov, S. V. Petropavlovsky, and V. P. Yakovlev, Phys. Scr. **93**, 114002 (2018).
12. M. I. Vaskovskaya, E. A. Tsygankov, D. S. Chuchelov, S. A. Zibrov, V. V. Vassiliev, and V. L. Velichansky, Opt. Express **27**, 35856 (2019).
13. M. Stähler, R. Wynands, S. Knappe, J. Kitching, L. Hollberg, A. Taichenachev, and V. Yudin, Opt. Lett. **27**, 1472 (2002).
14. E. A. Tsygankov, S. V. Petropavlovsky, M. I. Vaskovskaya, D. S. Chuchelov, S. A. Zibrov, V. V. Vassiliev, V. L. Velichansky, and V. P. Yakovlev, "Intensity nonlinearity of the error-signal frequency shift in the modulation spectroscopy of dark resonances and approaches to its reduction," arXiv, arXiv:2012.13731 (2020).
15. V. Shah, V. Gerginov, P. D. D. Schwindt, S. Knappe, L. Hollberg, and J. Kitching, Appl. Phys. Lett. **89**, 151124 (2006).