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Self-mixing sensing system based on an uncooled VCSEL-array: linking multichannel operation and enhanced performance

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We compare the performance of a self-mixing sensing system based on an uncooled monolithic array of 24×1 Vertical-Cavity Surface-Emitting Lasers (VCSELs) in two modes of operation: single active channel and the concurrent multichannel operation. We find that the signal-to-noise ratio (SNR) of individual self-mixing sensors in a VCSEL array is markedly improved by multichannel operation, as a consequence of the increased operational temperature of the sensors. The performance improvement can be further increased by manufacturing VCSEL arrays with smaller pitch. This has the potential to produce an imaging system with high spatial and temporal resolutions that can be operated without temperature stabilization.

OCIS codes: (280.4788) Optical sensing and sensors; (280.3420) Laser sensors; (140.7260) Vertical cavity surface emitting lasers.

Many systems utilise a monolithic array of semiconductor lasers to increase the capability and functionality of single channel systems [1–4]. Such systems are able to dramatically increase the amount of data that can be acquired within a certain time frame or the amount of time it takes to obtain a certain amount of data. This is particularly important in the context of biomedical and industrial applications that have unstable or dynamically changing flow velocities.

In recent times, there has also been increasing interest in acquiring images with a monolithic array of lasers using the self-mixing (SM) effect [3, 4]. This sensing technique is based on the interference of light reflected from an external target with the light inside the laser cavity, which leads to measurable changes in the output power and the laser junction voltage. This is an attractive setup as the laser is used as both the source and detector, which greatly reduces the complexity of the optical alignment and makes the system more compact.

Initially, it may seem that simultaneous multichannel operation of SM sensors may lead to problems common in other systems based on a monolithic array of lasers such as optical, electrical and thermal crosstalk (XT). A

fraction of light emitted from a vertical-cavity surface-emitting laser (VCSEL) in a dense monolithic array will, upon reflection from the external target, inevitably fall on the neighbouring elements in the array [5]. In a SM system based on such geometries optical XT may occur through the injection locking between different channels (VCSELs) of the array [6, 7]. However, this is extremely unlikely to occur in most applications as injection locking requires a number of conditions to be met including mutual coherence and mode matching. This may be further avoided by a small change in the operating temperature or injection current of the laser [8]. Electrical XT may also arise through electrical connections to the laser array but other systems have been developed where this form of XT is insignificant at frequencies below 1 GHz [1, 9, 10]. Electrical XT may also be caused by the sharing of carriers via resistive paths in the laser array itself although this can be circumvented with appropriate semiconductor isolation structures [11].

Based on the results from other laser array based systems [2], it may also be expected that the heat generated by multiple lasers may decrease the performance of individual SM sensors. Surprisingly, we find that the signal-to-noise ratio (SNR) of a monolithically integrated SM VCSEL sensor arrays is actually enhanced rather than reduced with multichannel operation. This is a consequence of the following phenomenon: maximum SNR

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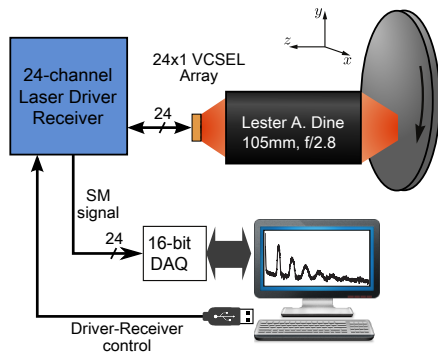


Fig. 1. Experimental setup for measuring velocity on a rotating disc. The disc is tilted around the vertical axis by 5° to produce a small velocity component in the direction of the laser beam.

achievable (over a range of operating injection currents) is increasing with the laser temperature, a result akin to that observed by Matharu et al. in a single channel system [12]. The remainder of this letter is therefore focused on describing an experiment that proves this phenomenon and discussing how the performance may be further enhanced through the array design.

The effect of multichannel operation in SM sensors was investigated in an uncooled 24×1 VCSEL array custom manufactured by Litrax Technology Co., Ltd with the system shown in Fig. 1. The VCSEL array was mounted in a surface mount ceramic package and individual VCSELs were wire-bonded to pins of the package. The VCSELs are based on proton implanted technology and have a pitch of $220 \mu\text{m}$. A FLIR i7 thermal imaging camera was used to examine the temperature profile of the array for different operational settings.

A single macro lens ($f=105 \text{ mm}$) was employed to focus all 24 laser beams onto a rotating disk. The target was placed 35 cm from the laser array, which resulted in a beam spacing of $220 \mu\text{m}$ and a magnification factor of 1. The laser array was oriented vertically. The aluminium disk, 10 cm in diameter, was sandblasted to provide a rotating diffusive target. The disk was driven by a DC servo motor with a 43:1 gear reduction controlled by an Elmo Whistle motor controller. The stability of the disk's angular velocity for the duration of the experiments was better than 1%, as established by monitoring the frequency of the motor's rotary encoder. A custom built 24-channel laser driver—receiver was used to individually bias each laser with a constant injection current. The SM signals were obtained through terminal voltage variations across individual VCSELs. The terminal voltage fluctuations were then individually amplified using 24 ac-coupled, single stage, low noise preamplifiers with gain $G = 100$. Additional stages of amplification with variable gain ($G = 64$ to 6400) were used to bring the signal to a level suitable for processing by a 16-bit data acquisition card.

Each channel had a sampling rate of 62.5 kHz. The

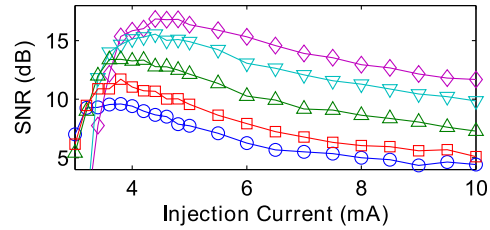


Fig. 2. SNR of central laser (Channel 12) versus injection current with different levels of current in neighbouring lasers. The current in the neighbouring lasers are all biased at the same current while the current of the central laser is varied. (circles - Single Channel, squares - Multichannel 2 mA, up triangles - Multichannel 5 mA, down triangles - Multichannel 8 mA, diamonds - Multichannel 10 mA).

power spectral density of the time domain signal was calculated in the LabVIEW programming environment to obtain the SM signal spectrum and 32 consecutive spectra were averaged. The Doppler frequency was extracted by fitting the power spectral density spectrum to a Gaussian distribution of Doppler components [13].

In this work, we are interested in uncooled operation of the laser array as Peltier devices consume high amounts of power and make a sensing system less compact and portable. For uncooled operation, the temperature of a single laser device may be increased by increasing the injection current or the amount of power dissipated as heat [14]. In array based operation, the heat generated by a single laser spreads to other lasers in the array. The resulting temperature rise from a neighbouring laser is inversely proportional to the pitch [15], which leads to the central lasers showing the highest rise in temperature when all lasers are operating simultaneously. To examine the effect of multichannel operation on the performance of a SM sensor we first measured the SNR of one of the central lasers (Channel 12) for a wide range of bias currents from threshold to 10 mA. We then remeasured the SNR for the same bias currents while turning on other lasers in the array. To maximise the temperature rise we simultaneously turned on the remaining 23 lasers in the array. These lasers, which we will subsequently referred to as the neighbouring lasers, were biased at the same injection current while the bias current of the VCSEL under investigation was changed. Figure 2 shows the SNR of the central (sensing) VCSEL over a range of bias currents.

Each curve corresponds to a different operating current in all neighbouring VCSELs. The well-known increase and subsequent decrease of SNR with bias current can be observed for all operating conditions [16, 17]. For single channel operation (neighbouring VCSELs not operating), the SNR increases rapidly above threshold before reaching a maximum. The SNR then gradually decreases as the injection current is increased beyond the current for the maximum SNR.

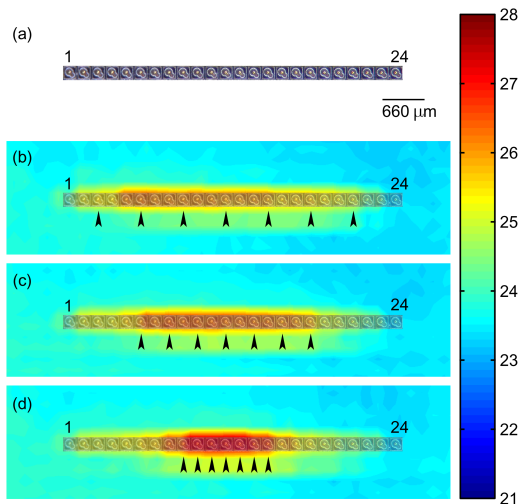


Fig. 3. Close up photo of the array and thermal images for the different separation distances used for the experiments in Fig. 4. a) Photo, b) 660 μm spacing, c) 440 μm spacing, d) 660 μm spacing. Channel 1 is located at the left hand side of the images.

When the currents in the neighbouring lasers were increased to 2 mA, which is below the threshold current of each laser, the SNR in the sensing VCSEL increased significantly. This indicates that the increase in SNR is not due to optical XT as the lasers have no observable signal level below the threshold current. Subsequent measurements on a probing station showed that the electrical isolation between adjacent elements was of the order of 5 $\text{M}\Omega$, which suggests that the increase in SNR was due solely to the temperature rise in the sensing laser. The injection current for the optimum SNR also slightly increases when the neighbouring lasers are turned on, which suggests that the initial temperature of the laser array is on the hot side of the parabolic threshold current temperature profile [12, 18]. Further increase in operating current of the neighbouring VCSELs leads to a monotonic increase in maximum achievable SNR.

To investigate this further, we measured the SNR of the central laser (Channel 12) while simultaneously operating six other lasers on the array. In each experiment, all seven lasers were equally spaced. Three different sets of equal spacing were investigated. The injection current in all of the neighbouring lasers was set to 10 mA. Therefore, in each experiment, the same electrical power was delivered to the laser chip. To examine this issue in more detail, we used a thermal IR camera to obtain the temperature profile of the array. Figure 3 shows a close-up photo of the array as well as the thermal images for the different separation distances used in the experiment.

Figure 4 shows the SNR of the central VCSEL as a function of injection current. Three curves correspond to three different separation configurations, with corresponding temperature distributions shown in Fig. 3. Clearly, the SNR increases as the separation distance

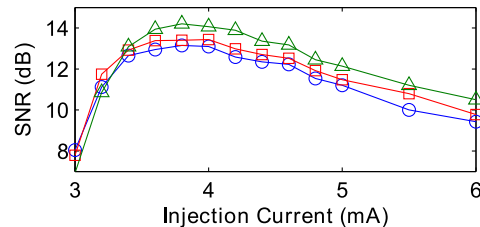


Fig. 4. SNR of central laser (Channel 12) versus injection current with simultaneous operation of six neighbouring lasers biased at 10 mA. There is an equal separation distance between lasers with the separation distance varying for different experiments. (circles - 660 μm spacing, squares- 440 μm spacing, triangles - 220 μm spacing).

between lasers decreases, which can be attributed to the higher temperature of the central (sensing) VCSEL due to the heating sources being concentrated nearer the sensing VCSEL.

A consequence of this result is that the SNR may be further improved by manufacturing an array with elements spaced more closely together. This would not only increase the spatial resolution of an imaging system based on this array, but also allow for a smaller lens to be used due to the smaller array size, making the whole optical system more compact. The temperature rise in the array may also be increased by increasing the element diameter as suggested by Osinski et al [15]. However, larger diameter VCSELs may exhibit multiple transverse modes, which can affect the accuracy and performance of SM sensors [19].

While a change in operating current and temperature strongly affects the SNR of the system it also affects the emission wavelength of the lasers. We show here that this substantial change in lasing wavelength has predictable, and almost negligible effect, on the Doppler frequency and calculated target velocity. The dependence of the lasing wavelength on current and heatsink temperature was measured by placing the laser chip in a temperature-controlled mount. Figure 5 shows the VCSEL wavelength dependence on current and temperature measured on a stand-alone VCSEL of the same design as the VCSEL array used in this work. Measurements were executed for a range of temperatures between 10 and 60 $^{\circ}\text{C}$ and currents up to 10 mA. Polynomial fit to these experiments can be conveniently represented by the following function:

$$\lambda(T, I) = 844.1 + 0.063T + 0.066I + 0.00029TI + 0.0128I^2, \quad (1)$$

where T is the heatsink temperature in $^{\circ}\text{C}$, and I is the laser current in mA, and λ is wavelength in nm. The change in lasing wavelength with current is mainly caused by heating of the laser cavity [20].

At each temperature—current pair (represented by

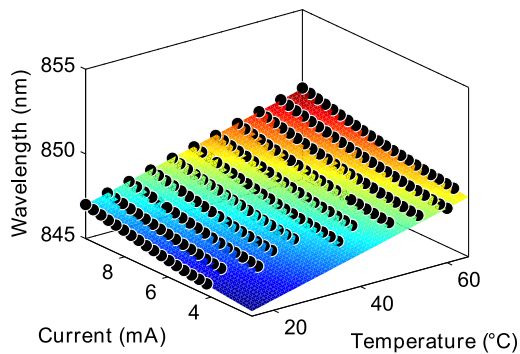


Fig. 5. Surface fit of the variation in wavelength with current and temperature to experimental data from stand-alone Litrax VCSEL.

black dots in Fig. 5) a SM Doppler spectrum was acquired and the Doppler frequency was extracted. The total shift in Doppler frequency caused by changes in current and temperature was 16 Hz (from 2.784 kHz to 2.768 kHz) which corresponds to a fractional change of approximately 0.6%. This systematic error may be removed by calculating the wavelength at any given point in the current—temperature space using (1).

Figure 3 shows that temperature variation under different operating regimes of our array is much smaller than the current—temperature range used in this experiment. Therefore, we can safely conclude that the effect of current and temperature change in an uncooled VCSEL array will not only be predictable and easily removable but shows negligible effect on the performance of such arrays. This means that there is no significant reduction in the accuracy of the velocity determination with multichannel operation of a SM array based sensor, which allows it to be used for a wide range of sensing applications.

In summary, we have compared the performance of single channel and multichannel operation of an uncooled single mode monolithic 24×1 VCSEL array in a SM sensing system. We found that the SNR of monolithically integrated SM sensor arrays is inherently enhanced through multichannel operation, as a result of the increased operational temperature of the sensor. This effect can be augmented by reducing the spacing between VCSELs on the array or increasing the diameter of each laser. Finally, the temperature rise due to multichannel operation had no significant effect on the measured Doppler frequency, which corresponds to no significant change in the accuracy of the measured velocity. These findings suggest that SM imaging systems based on VCSEL arrays have the potential to produce images with

high spatial resolutions at high frame rates. These features make parallel SM sensing systems especially attractive for biomedical and industrial applications where there are unstable or dynamically changing flow velocities.

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References

- [1] M. Maeda, C. Chang-Hasnain, A. Von Lehmen, H. Izapanah, C. Lin, M. Iqbal, L. Florez, and J. Harbison, *IEEE Photon. Tech. Lett.* **3**, 863 (1991).
- [2] T. C. Banwell, A. C. Von Lehmen, and R. R. Cordell, *IEEE J. Quantum Electron.* **29**, 635 (1993).
- [3] Y. Lim, M. Nikolic, K. Bertling, R. Kliese, and A. Rakic, *Opt. Express* **17**, 5517 (2009).
- [4] Y. Lim, R. Kliese, K. Bertling, K. Tanimizu, P. Jacobs, and A. Rakic, *Opt. Express* **18**, 11720 (2010).
- [5] F. F. Tsai, C. J. O'Brien, N. S. Petrovic, and A. D. Rakic, *Applied Optics* **46**, 2434 (2007).
- [6] E. K. Lau, X. Zhao, H.-K. Sung, D. Parekh, C. Chang-Hasnain, and M. C. Wu, *Opt. Express* **16**, 6609 (2008).
- [7] W. Yang, P. Guo, D. Parekh, and C. J. Chang-Hasnain, *Opt. Express* **18**, 20887 (2010).
- [8] R. Lang, *IEEE J. Quantum Electron.* **18**, 976 (1982).
- [9] G. Heise, *IEEE Photon. Tech. Lett.* **2**, 97 (1990).
- [10] S. Nakagawa, S.-Y. Hu, D. Louderback, and L. A. Coldren, *IEEE Photon. Tech. Lett.* **12**, 612 (2000).
- [11] M. Châteauneuf, A. G. Kirk, D. V. Plant, T. Yamamoto, and J. D. Ahearn, *Appl. Opt.* **41**, 5552 (2002).
- [12] R. Matharu, J. Perchoux, R. Kliese, Y. L. Lim, and A. D. Rakic, *Opt. Lett.* **36**, 3690 (2011).
- [13] M. Nikolić, D. P. Jovanović, Y. L. Lim, K. Bertling, T. Taimre, and A. D. Rakić, *Appl. Opt.* **52**, 3345 (2013).
- [14] K. Sato and M. Murakami, *IEEE Photon. Tech. Lett.* **3**, 501 (1991).
- [15] M. Osinski and W. Nakwaski, *IEEE J. Sel. Top. Quant. Electron.* **1**, 681 (1995).
- [16] P. Dean, Y. L. Lim, A. Valavanis, R. Kliese, M. Nikolić, S. P. Khanna, M. Lachab, D. Indjin, Z. Ikonić, P. Harrison, A. D. Rakić, E. H. Linfield, and A. G. Davies, *Opt. Lett.* **36**, 2587 (2011).
- [17] K. Rochford and A. Rose, *Opt. Lett.* **20**, 2105 (1995).
- [18] C. Chen, P. O. Leisher, A. A. Allerman, K. M. Geib, and K. D. Choquette, *IEEE J. Quantum Electron.* **42**, 1078 (2006).
- [19] J. R. Tucker, A. D. Rakic, C. J. O'Brien, and A. V. Zvyagin, *Appl. Opt.* **46**, 611 (2007).
- [20] G. Hasnain, K. Tai, L. Yang, Y. Wang, R. Fischer, J. D. Wynn, B. Weir, N. Dutta, and A. Cho, *IEEE J. Quantum Electron.* **27**, 1377 (1991).