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## 3D femtosecond laser writing of a microlens on a single mode polarization-stable VCSEL chip for miniaturized optical spectroscopy

Qingyue Li,<sup>a</sup> Vincent Raimbault,<sup>a</sup> Pierre-François Calmon,<sup>a</sup> Benjamin Reig,<sup>a</sup> Pierluigi Debernardi,<sup>b</sup> Heidi Ottevaere,<sup>c</sup> Jean-Baptiste Doucet,<sup>a</sup> Julien Roul,<sup>a</sup> and Véronique Bardinal<sup>a</sup>

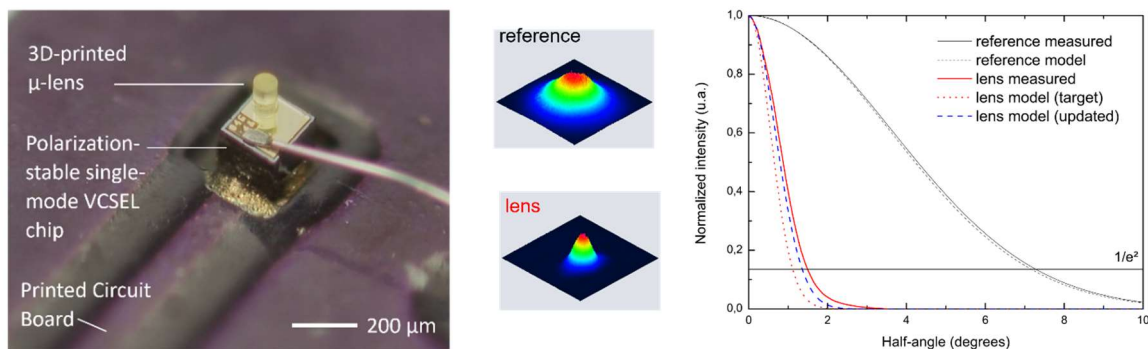
<sup>a</sup>University of Toulouse, CNRS, LAAS, Toulouse, France

<sup>b</sup>CNR-IEIIT c/o Politecnico di Torino, Torino, Italy

<sup>c</sup>Vrije Universiteit Brussel and Flanders Make, Department of Applied Physics and Photonics, Brussels, Belgium  
E-mail: bardinal@laas.fr

There is a growing demand for portable gas sensors, from both environmental and health sciences as well as the industry. Resonant optical sensors, in particular planar micro-resonators, combine high sensitivity and small footprint. The sensing principle of these guided-wave systems is based on a variation in the spectral response in the presence of the targeted molecules. The laser to be used as a probing source should emit a single-mode and polarization-stable beam and be tunable over at least few nanometers. NIR VCSELs are good candidates for these applications as they can be slightly tuned by simply playing on the current and their beam polarization can be stabilized by using a grating relief etched at their surface. However, polarization-stable single-mode VCSELs chips having a low divergence compatible with a use in a microsystem are not yet commercially available. The challenge relies in finding an accurate method to directly fabricate a collimation microlens on a small-sized VCSEL chip ( $200 \times 200 \times 150 \mu\text{m}^3$ ) at a post mounting stage (figure 1, left).

In this work, we demonstrate that 2-photon-polymerization 3D laser printing can be exploited to fabricate such a microlens with a writing time of only 5 minutes. We first optimized lens design and fabrication conditions to obtain a sufficient surface quality and a suited focal length. The VCSEL chip's divergence was then reduced from  $14.4^\circ$  to  $3^\circ$  (full angle at  $1/e^2$ ) (figure 1, right), corresponding to a beam spot size of  $55 \mu\text{m}$  at a distance of 2 mm (instead of  $\sim 250 \mu\text{m}$ , initially). These results are comparable to those obtained in a previous work that involved 3 different techniques and long thermal steps [1]. Moreover, a good agreement between experiments and Gaussian propagation modelling was obtained taking into account fabrication uncertainties and assuming a position of the initial beam waist  $3 \mu\text{m}$  beneath the VCSEL's output surface. This indicates that lens design could be further optimized and that a minimal divergence of  $2.5^\circ$  is fully achievable. Finally, the study of the spectral behavior of the lensed VCSEL submitted to an electrical current variation was studied. After lens integration, a reduction from 7 nm to 3 nm in the available single-mode spectral range was observed. We explained this behavior by computing the optical transverse mode losses and we proposed a specific design based on the same VCSEL wafer layout to extend the available single-mode tuning range and additionally improve the threshold conditions [2].



**Fig. 1** (left) Microlens fabricated on the VCSEL chip by 2-photon-polymerization 3D printing at a post-mounting stage, leading to a reduction of the divergence from  $14.4^\circ$  to  $3^\circ$  (right) Comparison of the normalized angular beam distributions of the reference and lensed VCSEL chips (solid lines: experimental, dotted lines: model).

### References

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