Enhanced Butt Coupling Efficiency of VCSELs into Hollow Core Fibre using a Graded Index Fibre Lens

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Abstract *We present an investigation into direct butt-coupled interconnection of hollow-core fibres to single-mode VCSELs operating at 850 nm. Our results show the coupling efficiency can be significantly improved from 10% to 69% using a graded-index fibre (GIF) based, all-fibre mode field diameter (MFD) converter.*

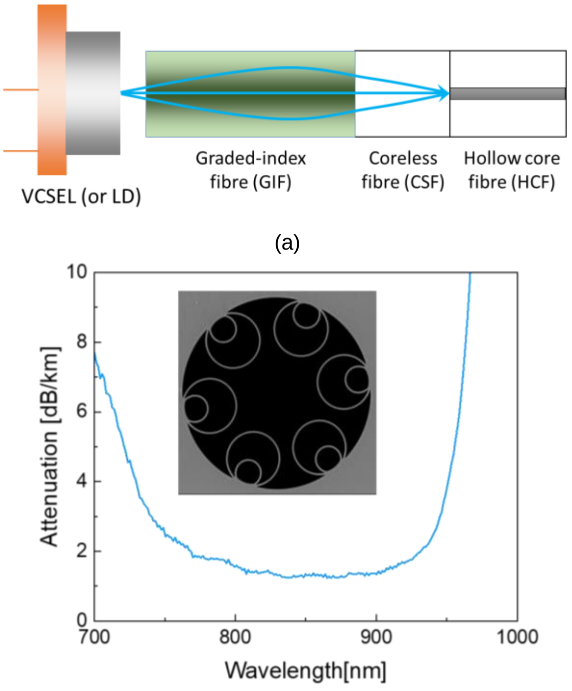
Introduction

The efficient coupling of light between laser diodes and optical fibres is critical for numerous photonic applications. While fibre coupled optical devices based on solid core fibres have been extensively researched, there are only limited reports on the coupling of laser diodes to hollow core fibres (HCFs) [1, 2]. For certain applications, even a short length of solid core fibre pigtail may not be suitable or cost-effective, especially at extreme wavelengths such as ultraviolet (UV) or mid-infrared (mid-IR) where the intrinsic glass attenuation is prohibitively high. HCFs have become increasingly popular at these wavelengths due to their low transmission loss and solarization-free UV transmission. Direct HCF interconnection without any significant intermediary length of silica fibre can enhance transmission stability and maintain beam quality. In addition, direct interconnection can be crucial in applications where ultimate latency is a key parameter, such as data center applications, where HCFs offer a solution to reducing latency and dispersion, while increasing spectral bandwidth and reach.

In this paper, we focus on the challenge of optical interconnection between VCSELs and HCFs, with a particular emphasis on the use of a direct butt coupling approach utilizing a graded-index fibre (GIF) lens. Our findings make a significant contribution to ongoing efforts to develop efficient, reliable, and cost-effective interconnection techniques for HCFs.

All-fibre MFD converter based on a GIF lens

To enhance the efficiency of fibre butt coupling we employed a GIF lens element at the input end facet of the HCF, as depicted in Fig. 1(a). This technique involves use of a single lens for image formation, with the size of the output plane image (in our case, we are concerned with the mode field diameter (MFD) of the beam) adjusted by changing the magnification ratio of the object. Our design incorportates a GIF as a compact lens element, in combination with a coreless fibre (CSF) segment which serves as a spacer. By selecting the appropriate lengths of both fibres, a compact all-fibre MFD converter can be readily constructed using a simple cleaving and fusion splicing procedure. Such a GIF-lens-based all-fibre structure has previously been used to reduce the splice loss between two dissimilar SMFs by adjusting their MFD mismatch [3], as well as for low-loss optical interconnection between dissimilar multicore fibres with different core pitch distances [4].



(a)

(b)

Fig. 1: (a) Schematic of the butt coupling setup for VCSEL coupling with HCF, enhanced with GIF. (b) SEM image and fibre attenuation of the HCF used in our experiments.

For our experiment, we chose a single mode VCSEL (LCV850SP2, Laser Components Ltd.) with a wavelength of 850 nm, a maximum output power of 1.4 mW, and an almost perfect Gaussian beam profile with a beam divergence of 22º. Note that the VCSEL was initially packaged in a hermetic TO-46 can housing, but we removed the protective glass window for microscopic imaging and direct butt coupling experiments. A state-of-the-art HCF with nested anti-resonant nodeless fibre (NANF) structure [5] was employed in this demonstration. Fig. 1(b) shows a cross-sectional scanning electron microscope (SEM) image of the fibre and the fibre loss spectrum. This HCF had an air-core diameter of 27 µm, a micro-structured cladding diameter of 75 µm, and an outer diameter of 204 µm. It comprised six nested, anti-resonant capillaries in the cladding, which enabled efficient, low-loss light guidance in the second anti-resonant window. The measured fibre loss was approximately 1.4 dB/km at 850 nm, which is lower than that of commercially available solid-core single-mode fibres (e.g., ~3.5 dB/km@850 nm for 780HP). In our experiment, we used a total length of 1.04 km HCF.

Simulation

To evaluate the performance of the proposed MFD converter design, we conducted simulations using the beam propagation method (BPM). We utilized a commercially available OM4 graded-index multimode fibre with a 50 µm core diameter as the GIF and determined that the optimal fibre segment lengths for the GIF and CSF for maximum coupling efficiency were 240 µm and 850 µm, respectively, to achieve maximum coupling efficiency. As shown in Fig. 2, the divergent light emitted from the VCSEL gradually converges after passing through the GIF, resulting in an increase in the coupling efficiency as the CSF length increases. This improvement in coupling efficiency is mainly due to the magnification process, which enlarges the MFD at the image plane. Our simulation indicates that this approach can enable coupling efficiency of approximately 90%. It is worth noting that the length of GIF plays a critical role in realising high coupling efficiency, making it essential to exercise special care when cleaving and splicing the GIF to ensure optimal performance.

Experiment

To validate the simulation, we fabricated an all-fibre MFD converter based on GIF. This converter was created by splicing a 240 µm segment of GIF with a segment of CSF at the end facet of the HCF. Given that the fibre segment lengths were in the range of hundreds of micrometres, precise cleaving and splicing of the optimized fibre lengths were necessary. However, during the fabrication process, we observed that the thin glass membranes of the HCF were susceptible to being deformed and retract a little into the fibre by the arc fusion during the CSF-HCF splice. To address this issue, we used a shorter CSF segment (700 µm instead of the initially planned 850 µm), assuming that the membrane collapse region is ~150 µm. We considered this region of tube retraction to effectively provide additional spacing between the GIF and HCF. Figure 3 shows a microscope image of the fabricated MFD converter, with the measured fibre segment lengths being 250 µm and 710 µm, respectively. Our precision cleaver provided for ~10 µm position accuracy.

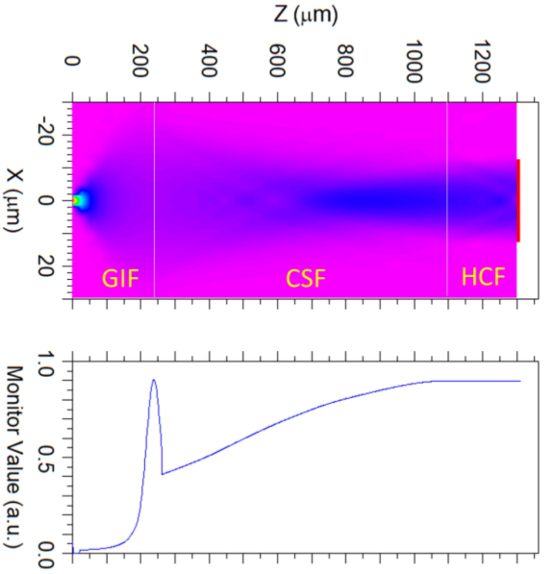


Fig. 2: BPM simulation of the proposed structure.

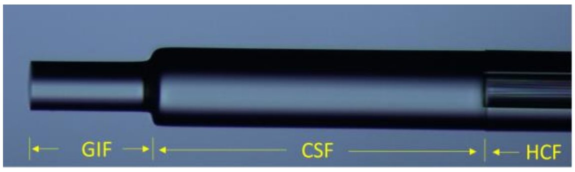


Fig. 3: Microscope image of the fabricated all-fibre MFD converter.

To test the butt coupling efficiency, the VCSEL was securely mounted onto a temperature-controlled laser mount, which was stabilized by a thermoelectric cooler with the temperature set to around 20 degrees. The HCF with the fabricated all-fibre MFD converter was positioned in a V-groove fibre holder which was mounted on a multi-axis stage to allow precise optical alignment. Using a microscope, we carefully aligned the VCSEL emitter and the fibre end, ensuring that they were in close proximity but without making physical contact. After achieving initial alignment, we used an optical power meter to finely adjust the alignment until maximum power output was reached in our butt coupling experiment. Using this MFD converter, we achieved a significantly improved coupling efficiency of ~69% (1.61 dB loss), approximately 7 times better than that achieved through direct HCF butt coupling (~10%). However, we noticed that the coupling efficiency was slightly lower than the theoretical 90% value (0.45 dB loss) from simulations. This may be due to dopant diffusion within the GIF and/or inaccurate assumptions about the microstructure collapse length during the fibre fusion splice process. We believe that this can be further optimized with better control of the fibre length and splice parameters.

To evaluate the axial displacement tolerance, we positioned the HCF at the point of maximum coupling efficiency with the VCSEL and then adjusted its position in the axial direction. As shown in Fig. 4(a), the coupling loss increased as the HCF was moved away from the emitter due to the increased MFD mismatch. We measured a ~5 µm axial displacement tolerance for 1 dB increase in loss. To analyse the lateral offset tolerance we conducted a two-dimensional (2D) scan of the HCF around the optimized position [14]. We scanned the fibre over an area of 50 µm by 50 µm and sampled on a 100 by 100 step grid. As depicted in Fig. 4(b), the measured 1-dB lateral tolerance was approximately 1.3 µm. This tight tolerance is mainly due to the reduced MFD, which required more careful active alignment to minimize the coupling loss. In Fig. 4(b), a distinct stripe line can be observed in the 2D contour plot. This stripe results from the metal wire used for electric connection (located approximately 75 µm away from the emitter).

Conclusion

In conclusion, in this study we successfully improved the butt coupling efficiency between a VCSEL and an HCF by using a graded index fibre lens. We observed that simple direct HCF interconnection (i.e. no lens) resulted in poor coupling efficiency due to the large MFD mismatch. However, the graded-index fibre lens significantly improved the coupling efficiency to ~69%, broadly consistent with the predicted value of ~90% from simulation. This indicates that the GIF lens is an effective solution for addressing the MFD mismatch issue in VCSEL-HCF interconnection. As a next step, we intend to extend our study to cover other wavelength bands, with a specific focus on the mid-IR and visible/UV wavelengths.

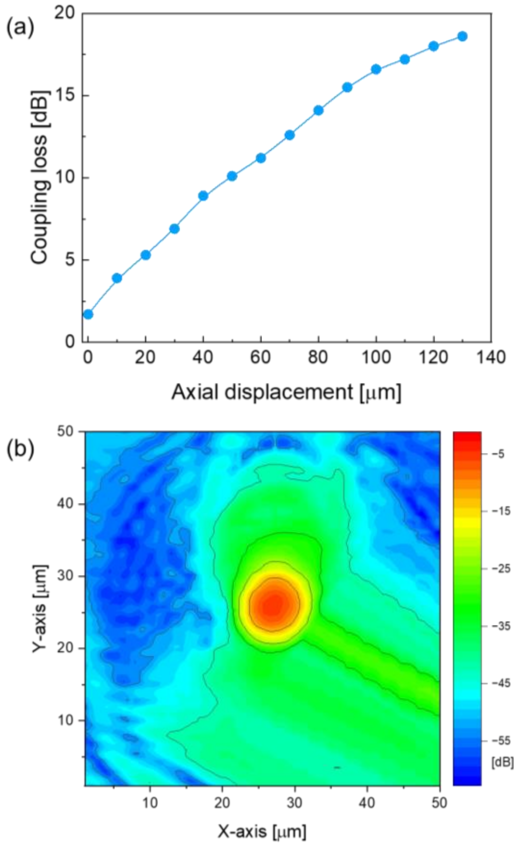


Fig. 4: Measured coupling loss according to (a) the axial- and (b) lateral offset.

Acknowledgement

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References

[1] K. Pierściński, G. Stępniewski, M. Klimczak, G. Sobczak, D. Dobrakowski, D. Pierścińska, D. Pysz, M. Bugajski, and R. Buczyński, Butt-coupling of 4.5 µm quantum cascade lasers to silica hollow core anti-resonant fibers, J. Lightwave Technol. 39 (2021) 3284-3290.

[2] B. Siwicki, R. M. Carter, J. D. Shephard, F. Yu, J. C. Knight, D. P. Hand, Negative-curvature anti-resonant fiber coupling tolerance, J. Lightwave Technol. 37 (2019), 5548-5554.

[3] P. Hofmann, A. Mafi, C. Jollivet, T. Tiess, N. Peyghambarian and A. Schülzgen, Detailed investigation of mode-field adapters utilizing multimode-interference in graded index fibers, J. Lightwave Technol. 30 (2012), 2289-2298.

[4] Y. Jung, J. Hayes, Y. Sasaki, K. Aikawa, S. U. Alam, and D. J. Richardson, All-fiber optical interconnection for dissimilar multicore fibers with low insertion loss, in Optical Fiber Communication conference (Optica Publication Group, 2017), paper W3H.2., https://doi.org/10.1364/OFC.2017.W3H.2

[5] H. Sakr, Y. Chen, G. T. Jasion, T. D. Bradley, J. R. Hayes, H. C. H. Mulvad, I. A. Davidson, E. N. Fokoua, F. Poletti, Hollow core optical fibres with comparable attenuation to silica fibres between 600 and 1100 nm, Nat. Communications 11 (2020), 6030.