Multi-Spot Fiber Lasers for Material Processing Applications

Yongmin Jung*[a], Natasha Vukovic[a], Christophe A. Codemard[a,b], and Michalis N. Zervas[a,b]

[a]Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
[b]TRUMPF Lasers UK Ltd, 6 Wellington Park, Tollbar Way, Hedge End, Southampton, SO30 2QU, UK
*ymj@orc.soton.ac.uk

ABSTRACT

We introduce a new approach for the generation of high-power multi-spot fiber lasers, employing square core fiber segments to enhance the efficiency of material processing. Utilizing an all-fiber strategy with single mode fiber– square core fiber (SMF-SCF) structures, our approach exemplifies notable progress in beam shaping technologies. Through laser drilling experiments on metals, the effectiveness of this technique is demonstrated, promising diverse applications in advanced manufacturing and industrial processes.

Keywords: Square core fibers, multi-spot beams, beam shaping

1. INTRODUCTION

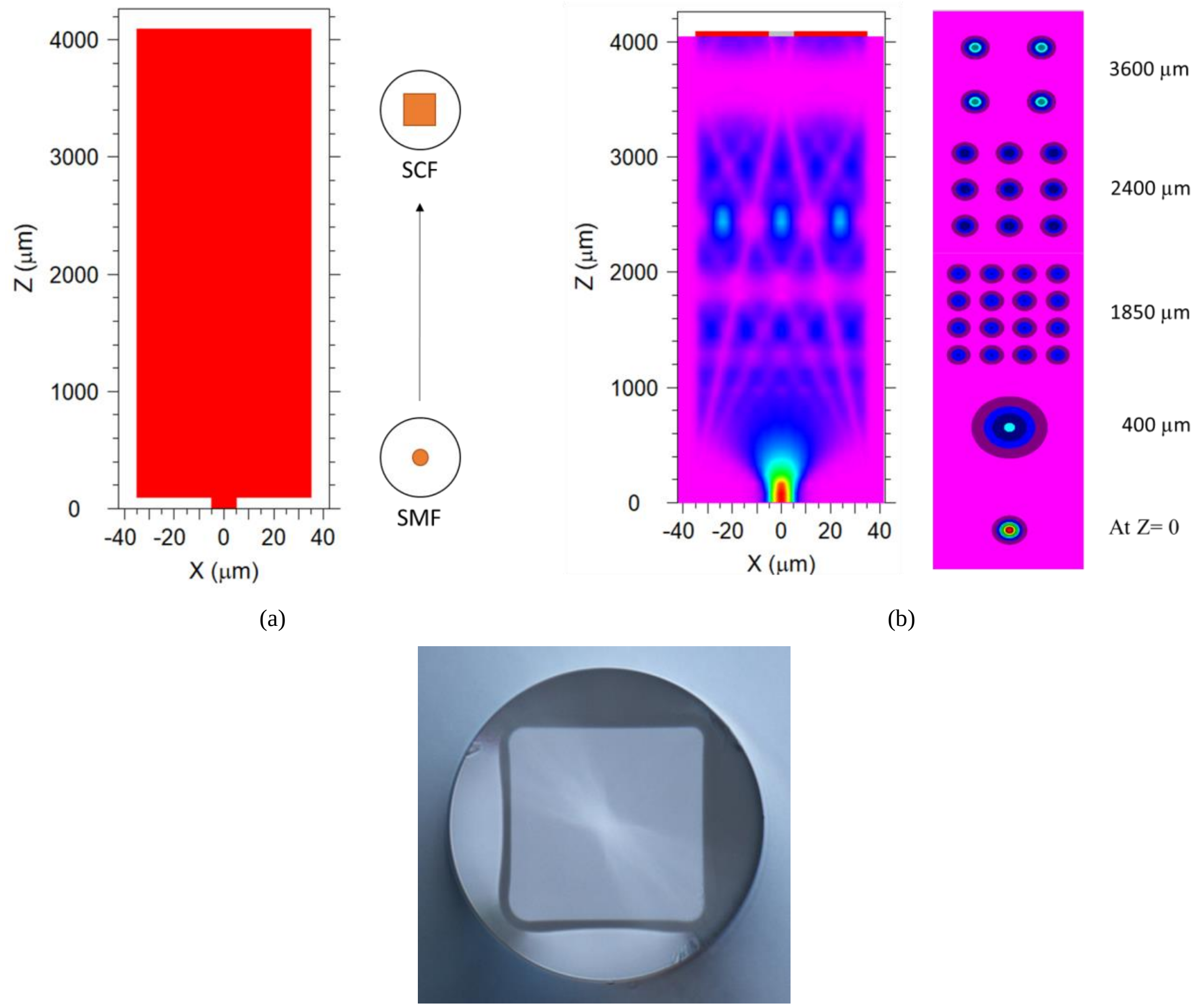
Fiber laser sources (FLs) [1] emerge as invaluable tools in advancing the shift towards a greener economy, thanks to their exceptional properties including high energy efficiency, compactness and reduced environmental impact. These attributes unlock new possibilities for applications in renewable energy. Their versatility and high productivity make them ideal for various material processing tasks, including metal cutting, drilling and welding. As we transition into the digital manufacturing era (Industry 4.0), there is a growing need for “smart” fiber laser sources capable of dynamically generating and manipulating structured laser beams for advanced material processing [2].

For example, multi-spot laser (MSL) enables parallel material drilling, thereby reducing cost and process time. For instance, in aerospace applications, MSL enhances engine performance and fuel efficiency and enables precise fuel delivery in automotive fuel injectors. Additionally, its applications extend to electronics manufacturing, medical devices, and precise machining. However, generating multi-spot laser beams traditionally requires complex and non-scalable methods using free-space optics, beam splitters, diffractive optical elements, or spatial light modulators. Multi-spot beams, albeit in a circular arrangement, have also been produced recently by using appropriate all-fiber mechanical transducers to transform the fundamental LP_{01} mode into a LP_{n1} mode (n=1,2,3,4,5) [3].

To address and overcome some of the challenges posed by these conventional methods, this paper introduces a new approach utilizing square core fiber segments to create static high-power multi-spot fiber lasers. This innovative all-fiber approach, utilizing SMF– SCF structures, provides a simpler, more efficient, and scalable solution for multi-spot laser drilling on metals. The incorporation of a multimode SCF enables the generation of multiple beam spots arranged in a square lattice. This configuration enhances control and efficiency in high-power fiber laser systems. Beyond addressing the limitations of traditional methods, this proposed technique marks a significant advancement in beam shaping technologies, broadening its applicability in various advanced manufacturing and industrial processes.

2. SMF-SCF STRUCTURES

The proposed structure, denoted as SMF-SCF, is depicted in Fig. 1(a). This configuration involves the simple splicing of a SCF section at the end of SMF. In contrast to conventional single mode fiber – multimode fiber (SMF-MMF) structures [4, 5], where guided modes along the length of the MMF generate various spatial beam patterns with circular symmetry, the introduction of a multimode SCF opens up new possibilities by enabling the generation of multiple beam spots arranged in a square lattice [6, 7]. The SCF segment, where light is selectively excited at the center from the SMF, served as a key element in shaping the laser beam into multiple spots. The structure was initially analyzed using beam propagation methods, unveiling the potential for achieving various multi-spot profiles within a square lattice. As illustrated in Fig. 1(b), the input single mode beam from the SMF begins to diverge upon entering the multimode SCF. However, it subsequently undergoes multimode interference, resulting in clearly defined multiple beam spots - 4×4, 3×3, and 2×2 beam patterns at SCF lengths of 1850, 2400 and 3600 µm. For even longer SCF lengths, perfect self-imaging of the original beam (i.e. single mode single spot beam) can be reconstructed but it is not the primary focus of this paper. In our specific example, a 70×70 µm core SCF with a numerical aperture (NA) of 0.22 (manufactured by CeramOptec) was employed, and the cross-section of the SCF is shown in Fig. 1(c). The input fiber is a single mode fiber operating at 1060 nm with a core diameter of ~10 µm and a NA of the core at 0.085. The separation between beams is primarily determined by the physical core size of the SCF, with observed weak wavelength dependency. This configuration not only underscores the versatility of the proposed SMF-SCF structure in generating multi-spot laser beams but also emphasizes the robustness and consistency of the achieved spatial patterns across varying SCF lengths.



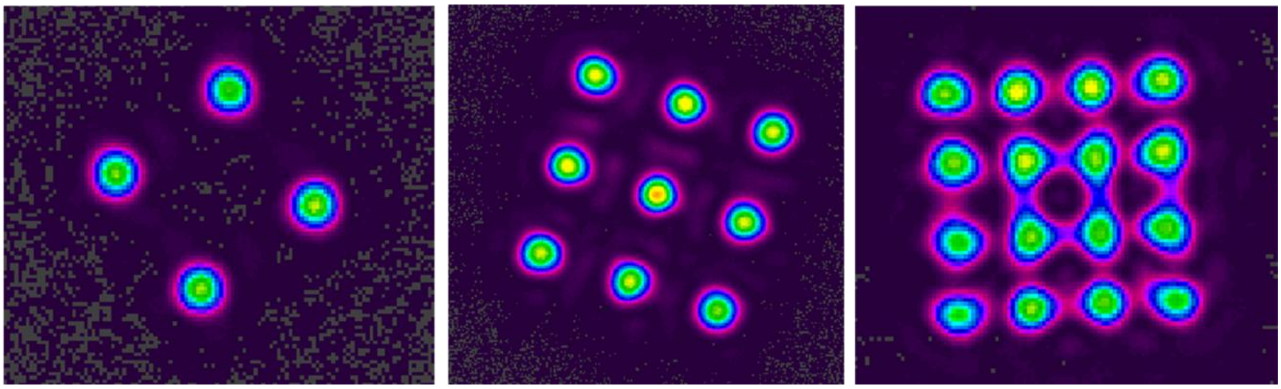
(a) (b)

(c)

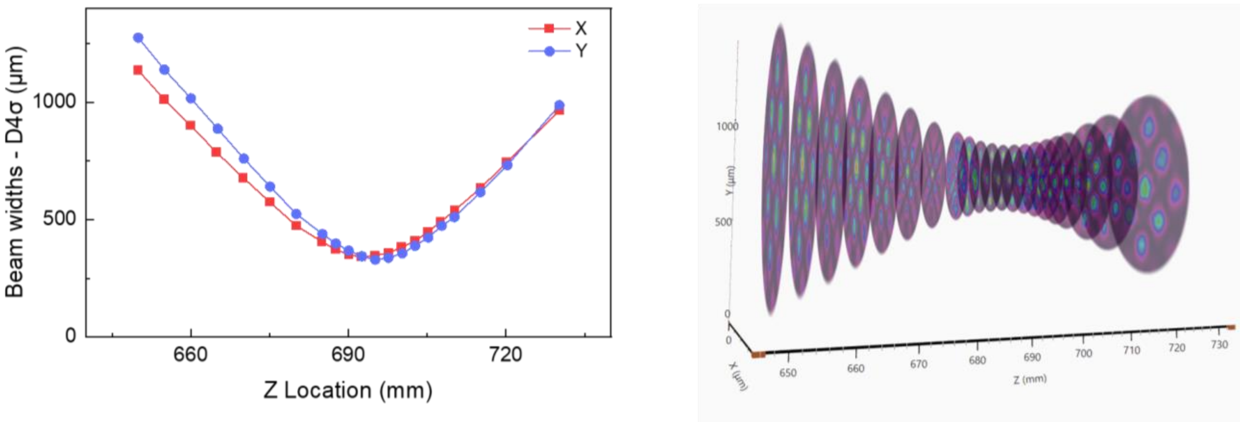
Figure 1. (a) The proposed SMF-SCF structure for multi-spot beam generation. (b) Beam propagation simulation of the structure and its beam intensity at different locations along the structure. (c) Cross-section of SCF from Ceramoptec used in our experiment.

3. MULTI-SPOT BEAM PROFILES

To validate the effectiveness of our proposed SMF-SCF structures in generating multi-spot laser beams, a comprehensive series of experiments was conducted, involving the fabrication of various SMF-SCF structures. Each structure featured a different SCF segment length, enabling the exploration and characterization of various multiple beam spots. The interference patterns, significantly influenced by the length of the SCF segment, necessitated precise cleaving and splicing of the optimized fiber lengths. To achieve the required precision, we employed a cutting-edge cleaver equipped with a micro-positioner, providing ~10 µm position accuracy. This precision is crucial to ensure that the fabricated SMF-SCF structures meet the specific requirements for generating diverse multi-spot patterns. The near field patterns of the fabricated samples were measured at 1060 nm, as shown in Fig. 2(a). The intensity patterns obtained at focal points demonstrate the existence of 2×2, 3×3, and 4×4 multi-spots, confirming our simulations. Additionally, we launched the output beam from the SMF-SCF structure into the entrance lens of an Ophir BeamSquared® beam profiler, allowing us a comprehensive analysis of the spatial intensity profile of the laser beam at a specific plane perpendicular to its propagation direction. In the focused region, the multi-spot beam patterns were clearly visible, highlighting the precision and control achieved through our SMF-SCF structures. It is noteworthy, however, that while the multi-spot beam pattern is distinguishable, the beam quality measurement (M^2) for 2×2, 3×3, and 4×4 beams were approximately 6.6, 8, and 7, respectively. Fig. 2(b) visually illustrates the beam evolution of the 2×2 beam near the focus, providing a representation of the spatial patterns. This illustration emphasizes the distinct 2×2 beam within the Rayleigh range, transitioning to a 3×3 beam (far-field image of the 2×2 beam) beyond this range. Importantly, this observation highlights our ability to create multiple beam spots within the Rayleigh range, albeit with a shorter Rayleigh range due to significant beam divergence resulting from the multi-beam interference effect. This insight contributes to our understanding of the spatial characteristics and limitations associated with the multi-spot beam patterns generated through our innovative SMF-SCF structures.



(a)

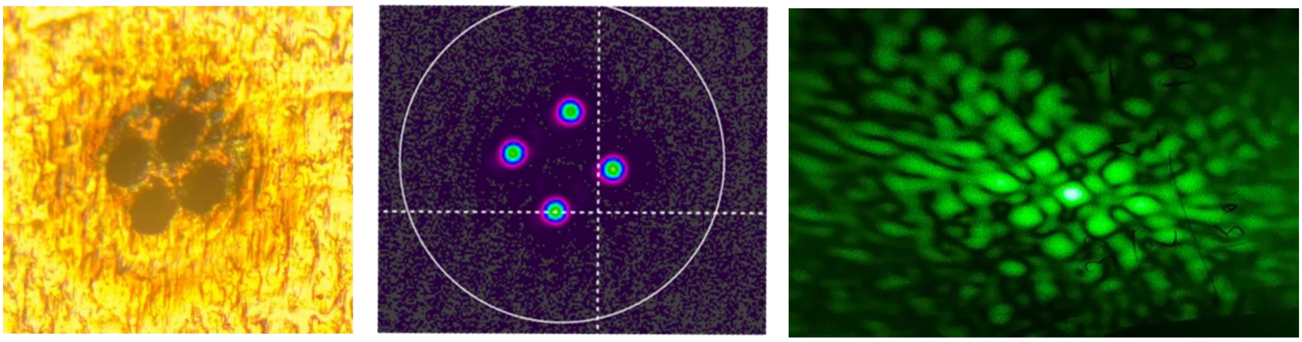


(b)

Figure 2. (a) Intensity patterns obtained from the M^2 measurements at focal points for 2×2, 3×3 and 4×4 SMF-SCF. (b) Visualization of beam evolution based on M^2 measurement for the 2×2 SMF-SCF corresponding to M^2 of 6.6.

4. MATERIAL PROCESSING APPLICATIONS

To explore the potential of material processing using a multi-spot beam, we employed a 1064 nm pulsed laser consisting of a fibre pigtailed microchip laser followed by a single fibre amplifier, emitting 1.2 ns pulses at a repetition rate of 100 kHz, with an output peak power of ~5 kW. The output fibre has a single mode 10μm core that was directly spliced to the SMF-SCF structure. The multi-spot beam is then focused into copper and aluminium foils to drill holes. By adjusting the distance from the focal point of the emitted multi-spot beam, we were able to maintain the desired beam patterns. Figure 3(a) displays our preliminary results from drilling a 10 μm-thick copper foil, where four clear holes with a diameter of ~4 μm were observed. To verify the complete drilling of holes, we illuminated the sample with a collimated green laser beam and observed the resulting diffraction patterns. The observed diffraction pattern aligns well with our theoretical expectations, confirming the successful material ablation and providing insights into the quality and uniformity of the drilling features. Notably, our investigations into material processing applications are ongoing, with a specific focus on expanding the range of materials and exploring additional parameters for optimizing the process. The ability to generate multi-spot patterns with precise control opens up avenues for intricate material processing tasks, including micro-machining, surface structuring, and precise ablation.



(a) (b) (c)

Figure 3. (a) Drilled holes of 10 μm thick copper foil at focus with a 2×2 SCF. (b) Measured beam intensity at beam waist (scaled) for 2×2 SCF and (c) diffraction pattern from the 2×2 holes when illuminated with a green laser.

5. CONCLUSION

In conclusion, we have demonstrated the efficacy of an all-fiber SMF-SCF structure for generating multi-spot fiber laser beams by incorporating square core fiber segments at the end of a high-power single mode fibre laser. Through this innovative approach, we showcased the generation of diverse multi-spot beam patterns and highlighted the practicality of our approach in material processing applications, specifically in precision hole drilling in copper foils. The scalability, efficiency, and versatility of our technique represent significant advancements in beam shaping technologies, suggesting potential implications for advanced manufacturing and industrial processes.

ACKNOWLEDGEMENT

This work was supported in part by the EPSRC funded “Smart Fibre Optics High-Power Photonics (EP/W028786/1).

REFERENCES

[1] M. N. Zervas and C. A. Codemard**,** “High power fibre lasers: a review,” IEEE J. Quantum Electron. 20, 0904123 (2014).

[2] M. N. Zervas, “Bright future for fibre lasers?,” Laser systems Europe, 41, 12 (2018).

[3] N. Vukovic et al, “Multi-kW fiber laser with azimuthal mode output beam for advanced material processing,” Proc. SPIE vol. 11266, 1126618 (2020).
[4] Lucas B. Soldano and Erik C. M. Pennings, “Optical multi-mode interference devices based on self-imaging: principles and applications,” J. Lightwave Technol. 13, 615-627 (1995).
[5] Yiğit O. Yilmaz, Alok Mehta, Waleed S. Mohammed, and Eric G. Johnson, "Fiber-optic beam shaper based on multimode interference," Opt. Lett. 32, 3170-3172 (2007).
[6] Ziyang Zhang, Julia Fiebrandt, Dionne Haynes, Kai Sun, Kalaga Madhav, Andreas Stoll, Kirill Makan, Vadim Makan and Martin Roth, “Fiber-based three-dimensional multi-mode interference device as efficient power divider and vector curvature sensor,” J. Opt. 20, 035701 (2018).
[7] Kun Wang, Xingchen Dong, Patrick Kienle, Maximilian Fink, Wolfgang Kurz, Michael H. Kohler, Martin Jakobi, and Alexander W. Koch, “Opticla fiber sensor for temperature and strain measurement based on multimode interference and square-core fiber,” Micromachines, 12, 1239 (2021).