EPJ Web of Conferences **287**, 06025 (2023) https://doi.org/10.1051/epjconf/202328706025
*EOSAM 2023*

# Full-beam spatial coherence measurements of supercontinuum generation in multimode fibers

*Jiaqi Li*[1,*], *Piotr Ryczkowski* [1], and *Goëry Genty* [1]
[1]Photonics Laboratory, Tampere University, Tampere, Finland

**Abstract.** We study experimentally the spatial coherence across the full spatial beam profile of supercontinuum light generated in both in graded-index and step-index multimode fibers. We observe a decrease of the coherence area with an increase of the injected pump power. Numerical simulations based on linearly polarized modes and mode coupling theory are in good agreement with our experiments and indicate that the decrease of coherence area is strongly related to a change in the modal amplitude distribution.

## 1. Introduction

The study of nonlinear dynamics in multimode fibers (MMFs) has recently attracted significant attention, including e.g. parametric instabilities [1], supercontinuum generation (SC) [2], multimode solitons [3], and beam self-cleaning [4,5]. Beam self-cleaning has been observed in dissipative systems such as Raman or Brillouin scattering [3], but perhaps more intriguingly it has also been seen in conservative nonlinear systems with a Kerr nonlinearity [4], where the quasi-Gaussian spatial intensity distribution at the fiber output has been attributed to nonlinear coupling between multiple transverse modes. Attempts have been made to explain the underlying physical mechanism behind beam self-cleaning [5], and mode decomposition methods to evaluate the fraction of energy in different modes have also been developed for this purpose [6,7].

Here, using a wavefront folding interferometer [8], we characterize the spatial coherence across the full beam of a SC generated in both graded-index (GRIN) MMF and step-index MMF. We measure the spatial coherence as a function of injected power, and we observe that the coherence area is reduced when the injected power is increased although the spatial intensity of the beam at the fiber output always exhibits a near-Gaussian clean profile. Numerical analysis using linearly polarized (LP) modes and mode coupling theory is shown to reproduce qualitatively our experiments, indicating that the coherence area decrease arises essentially from energy transfer towards higher-order modes.

## 2. Experiment setup

Our experimental setup is shown in Fig. 1. A SC is generated by injecting sub-ns pulses at 1545 nm with multi-kW peak power from a Q-switched laser into 2 m long GRIN MMF and step-index MMF both with 50 µm core size. Note that the pump laser includes a short single-mode fiber patchcord which is directly connected to the MMF such that light is essentially injected into $LP_{0M}$ modes where M is an integer. We also verified that the SC is essentially generated in the MMF (both GRIN and step-index). The SC light is directed to a wavefront folding interferometer where the beam is flipped along the horizontal x-coordinate, allowing to measure the degree of spatial coherence $g$ as a function of distance $\Delta x$ from the beam center and vertical y-coordinate [8]:

$$g(\Delta x, y) = \frac{\langle E\left(\frac{\Delta x}{2}, y\right) \cdot E^*\left(-\frac{\Delta x}{2}, y\right)\rangle}{\sqrt{\langle\left|E\left(\frac{\Delta x}{2}, y\right)\right|\rangle^2 \cdot \langle\left|E^*\left(-\frac{\Delta x}{2}, y\right)\right|\rangle^2}} \quad (1)$$

where $E$ denotes the electric field amplitude and * marks the complex conjugate. The interference pattern is measured across the beam with a camera as a function of optical path difference and the degree of spatial coherence is then extracted at each pixel of the camera from the interferogram contrast at zero-path difference.

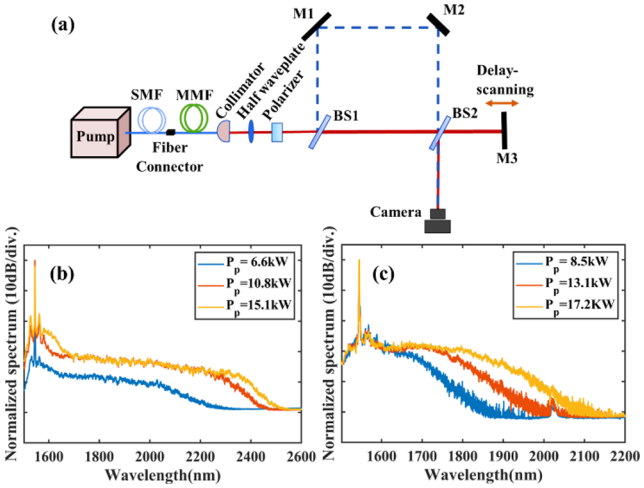


**Fig. 1.** (a) Experimental setup. BS: beam splitter, M: mirror, SMF: single-mode fiber patchcord, MMF: multimode fiber. SC spectra generated in the GRIN (b) and step-index (c) MMFs.

## 3. Experiment results

SC spectra were measured for different injected peak power (see Fig. 1(b,c)) and for each injected power the spatial coherence of the output beam was characterized in a 10 nm spectral band centered at 1640 nm by using a spectral filter. The far-field spatial intensity distribution of the beam as a function of increasing pump power in the GRIN and step-index MMF is shown in Figs. 2(a-c) and 3(a-c), respectively. The measured spatial coherence is illustrated in Figs. 2(e-f) and 3(e-f). One can see that, both for the GRIN and step-index MMF, the spatial intensity distribution exhibit a near-Gaussian clean intensity profile and that the beam size reduces when the peak power is increased. Correspondingly, the spatial coherence area decreases for increased peak power. These results seem to indicate that the relative fraction of energy in higher-order

* Corresponding author: jiaqi.li@tuni.fi

modes grows as the pump is increased, and this independently of the type of MMF.

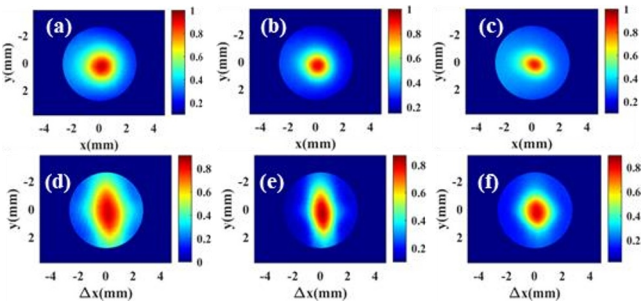


**Fig. 2.** Far-field spatial intensity distributions (a-c) and corresponding spatial coherence (e-f) of SG generated in GRIN-MMF for injected peak power of 8.5 kW, 13.1 kW and 17.2 kW.

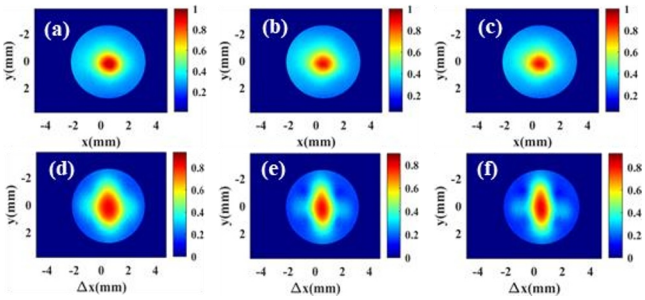


**Fig. 3.** Far-field spatial intensity distributions (a-c) and corresponding spatial coherence (e-f) of SC generated in step-index MMF for injected peak power of 8.5 kW, 13.1 kW and 17.2 kW.

To confirm our experimental observations, we numerically simulated the spatial coherence of the beam for step-index MMF and GRIN fibers. Our model uses LP modes [9] whose relative amplitudes are obtained from the coupling condition and modal expansion method [10]. Modal distribution at the output can be predicted from mode coupling theory [10] and the resulting spatial coherence can be computed as shown in Figs. 4 (GRIN MMF) and 5 (step-index MMF). For both types of fiber, the numerical analysis indicates that the fundamental mode is always dominant, in agreement with a near-Gaussian spatial intensity profile. However, as the injected power is increased, the energy fraction in high-order modes increases at the expense of that in the fundamental mode, leading to a decrease in the coherence area.

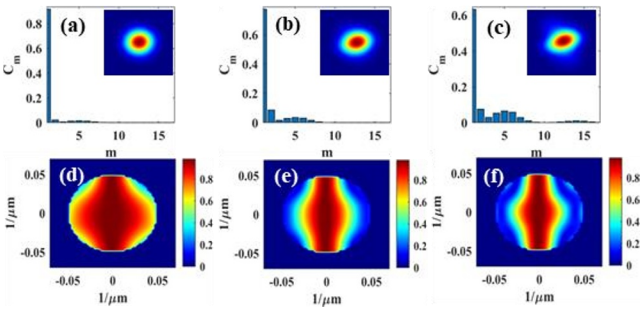


**Fig. 4.** Simulation results for GRIN MMF. (a-c) are the modal amplitude distribution and the insets are the far-field beams with the corresponding amplitudes. (d-f) show the corresponding spatial coherence.

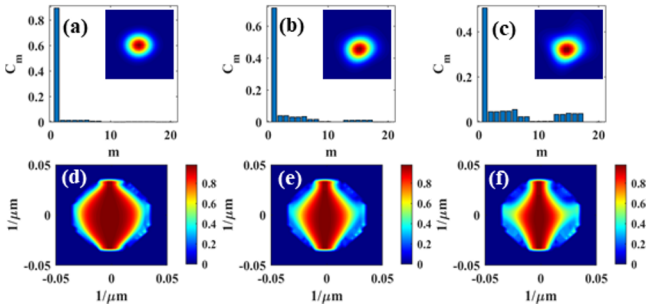


**Fig. 5.** Simulation results for step-index MMF. (a-c) are the modal amplitude distribution and the insets are the far-field beams with the corresponding amplitudes. (d-f) show the corresponding spatial coherence.

## 4. Conclusion

Using a wavefront folding interferometer, we have reported measurements of spatial coherence across the full beam of both GRIN and step-index MMFs in the highly nonlinear regime. We have observed a significant decrease in the spatial coherence area as the injected pump power is increased. Numerical analysis based on LP modes shows that a higher relative power fractions induces a decrease of coherence area, in agreement with the experiments. These seem to indicate that the contribution of higher-order modes to the overall spatial intensity is enhanced when the input power is increased.

## References

1. W. H. Renninger and F. W. Wise, *Nat. Commun*. **4**, 1719 (2012)
2. Z. Eslami *et al*., *Nat.* Commun. **13**, 2126 (2022)
3. N. B. Terry, T. G. Alley, and T. H. Russell, *Opt. Express* **15**, 17509-17519 (2007)
4. K. Krupa *et al*., *Nature Photonics* **11**, 237-241 (2017)
5. H. Pourbeyram *et al*., *Nat. Phys*. **18**, 685-690 (2022)
6. M. Zitelli *et al*., arXiv 2212.12882 (2022)
7. M.D. Gervaziev *et al*., *Laser Phys. Lett.* **18**, 015101 (2020).
8. M. Koivurova, H. Partanen, J. Lahyani, N. Cariou, and J. Turunen, *Opt. Express* **27**, 7738-7750 (2019)
9. A. Ghatak and T. Krishna. *An introduction to fiber optics*. Cambridge University Press (1998)
10. E. Hernandez *et al*., *J. Opt. Soc. Am. B* **38,** A36-A50 (2021).