# Beam-by-beam Kerr clean-up in multimode optical fibres - INVITED

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**Abstract.** We propose and demonstrate the concept of beam-by-beam cleaning in multimode optical fibres, i.e., the increase of the spatial quality of an intense laser beam, induced by a relatively weak, quasi singlemode seed beam. This effect, which relies on the Kerr nonlinearity of the fibre, is quite efficient: a seed beam is capable of providing a bell-shape to a ten times more powerful beam. Our results pave the way for the development of a new class of all-optical switching devices for intense laser beams.

## 1 Introduction

Singlemode fibres (SMF) have been historically preferred to multimode fibres (MMF) for virtually all applications, from telecommunications to fibre lasers. This has occurred in spite of the fact that MMF have several advantages when compared to SMF, e.g., MMF can ensure the propagation of higher energy light pulses, and may transmit more complex information, giving rise to the so-called space-division-multiplexing technologies. The reason behind the success of SMF over MMF is mostly ascribable to the high spatial quality of the beam at the output of SMF, owing to the guiding of a sole mode. To the contrary, multimode interference and random coupling result in a speckled beam profile at the output of MMF.

Such a paradigm, however, was broken by the discovery of Kerr beam clean-up, which is usually referred to as the spatial beam self-cleaning (BSC) effect [1]. As its name anticipates, BSC exploits multimode interactions in graded-index (GRIN) fibres, which are provided by the Kerr nonlinearity of the material, for producing a bell-shaped beam at the fibre output.

The possibility of delivering high spatial quality beams has recently made it possible to develop a whole new class of MMF-based technologies, e.g., singlemode-like output multimode fibre lasers [2] and beam delivery for high-resolution nonlinear multimode imaging [3].

Since BSC is a nonlinear effect, its manifestation requires the input power to overcome a certain threshold value ($P_c$), whose typical value is of the order of a few kWs, when dealing with Gaussian-like laser beams injected straight into the core of a few meters long standard GRIN MMF. The value of $P_c$ varies with the laser-fibre coupling conditions. In particular, it has been shown that on-axis coupling favours BSC, whereas beams injected into the fibre with a tilted angle ($\theta$) require higher powers to trigger BSC [4]. Moreover, for $\theta \neq 0$, injections with an off-set with respect to the fibre axis provide the beam with a transverse orbital angular momentum, which may hinder BSC [5].

Here, we generalize the paradigm of BSC, from a self-induced to an externally driven effect. To this purpose, we make use of different coupling geometries, in order to exploit the Kerr nonlinearity and generate a BSC-like process, which involves more than a single beam. Our coherent beam combining results show that a relatively weak BSC seed beam can be used, for controlling the spatial quality of an intense beam at the fibre output, thus demonstrating the brand new idea of beam-by-beam Kerr clean-up.

## 2 Experimental framework

We carried out an experiment where two orthogonally polarized laser beams of 60 ps of duration and 1064 nm of wavelength were simultaneously injected into the core of a 2.5 m long 50/125 GRIN fibre, whose fundamental mode has a Gaussian-like shape with a width of 6.33 μm. A first beam, which we dub the seed, is injected straight onto the fibre core, so that a bell-shaped beam is obtained at the fibre output, for input peak powers above 1.5 kW. Whereas the direction of the second beam, which is referred to as the reservoir, forms an angle θ≈2°, with no off-set with respect to the fibre axis. In this way, we could inject into the fibre a reservoir beam that carries a power of 138.5 kW, without experiencing any BSC. The synchronization between the two beams was ensured by means of a micrometric slit: in this way, we could investigate both the conditions of fully in-sync and out-of-sync beams.

## 3 Results

In order to demonstrate the principle of beam-by-beam Kerr clean-up, we kept the reservoir beam with a fixed power of 138.5 kW, while varying the power of the seed

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beam. The result of the experiment is shown in Fig. 1. Specifically, we plot (as a function of the input peak power) the correlation ($Cor$) between the intensity profile of the beam at the fibre output ($I$), which was measured by means of a CCD camera, and the intensity of the fundamental mode ($I_0$), i.e.,

$$Cor = \frac{\int dx\, dy\, I(x,y) I_0(x,y)}{\sqrt{\int dx\, dy\, I^2(x,y) \int dx\, dy\, I_0^2(x,y)}}. \qquad (1)$$

In Fig. 1a, we report the case where the sole seed beam is injected, i.e., the beam which experiences BSC. As it can be seen, $Cor$ increases with input peak power: the beam has always a radially symmetric shape (cfr. the insets of Fig. 1a). Whereas in Fig. 1b we illustrate the variation of $Cor$, when both the seed and the reservoir beam are simultaneously injected into the fibre core. Here we consider two different experimental conditions, i.e., when the beams are in-sync (empty circles), and when they are out-of-sync (full circles), respectively. As it can be seen, the curves that interpolate the two sets of data follow different trends. Whenever the beams are in-sync, $Cor$ increases with input power. Whereas, in the absence of synchronization, the value of $Cor$ remains practically constant, whenever the total peak power is varied. Fig.1b provides the fingerprint of the beam-by-beam Kerr clean-up effect. The significant increase of the beam quality of the combined beam, that is induced by the presence of the seed beam, may also be appreciated by the naked eye, when comparing the two black framed insets in Fig. 1b.

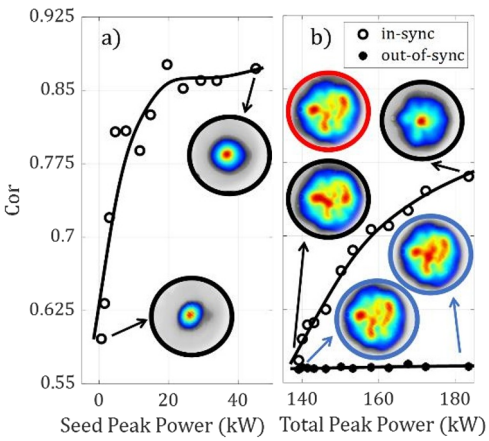


**Fig. 1.** Experimental demonstration of the beam-by-beam Kerr clean-up effect, when the peak power of the reservoir beam is kept constant to 138.5 kW. (a) Increase of $Cor$ with the peak power, when injecting the sole seed beam. (b) Evolution of $Cor$ when simultaneously injecting the seed and the reservoir beam. The solid lines in (a) and (b) are guides for the eye. The insets in (a) and (b) represent the beam profile at the fibre output, corresponding to the experimental data indicated by an arrow. The red framed inset in (b) is the output profile that is obtained when injecting the reservoir beam only.

We emphasize that the different slope of the two curves in Fig. 1b clearly indicates that the cleaning effect is of a nonlinear nature, and it is not due to, e.g., an artefact of the camera, whose colour scale might be dominated by the high energy density of the seed beam. In fact, since the exposition time of the camera is much longer than the laser repetition rate, the total power that reaches the camera is the same, regardless of the synchronization among the two beams. In this regard, one may notice that the out-of-sync output intensity profiles (blue framed insets in Fig. 1b) fully coincide with the superposition of the output intensity profile of the sole seed beam (insets in Fig. 1a) with that of the sole reservoir beam (red framed inset in Fig. 1b).

Note that the maximum value of power in Fig. 1a and 1b is 45 kW and 183.5 kW, respectively: their ratio R is of about 4. However, for the case in Fig. 1b one can reasonably well identify the presence of a clean beam with a value of Cor above 0.7. Since 153.2 kW is the minimum total peak power for which Cor > 0.7, the seed and reservoir beams have a power of 138,5 kW and 14.7 kW, respectively. This means that only about 10% of the reservoir power in the seed beam is sufficient to achieve the beam-by-beam Kerr clean-up effect, cfr. Fig. 1b. This indicates that the effect may enable efficient coherent combining of different intense laser beams with the same carrier wavelength but highly different beam quality, leading to a combined high-quality beam [4].

## 4 Conclusion

In conclusion, we introduced and experimentally demonstrated the concept of beam-by-beam Kerr clean-up in MMF. Specifically, we showed that a relatively weak, nearly singlemode seed beam can be exploited for controlling the spatial quality of a different, highly multimode intense beam at the fibre output.

Remarkably, within our experimental conditions, we found that the seed beam may carry a power which is as low as one tenth of the reservoir beam power, and still induce the clean-up of the combined beam.

Our results provide a leap forward in the transition from single- to multimode photonics [6]. Indeed, because of its all-in-fibre nature, beam-by-beam Kerr clean-up may naturally find applications to space-division-multiplexed fibre networks, and to mode-locked MMF lasers.

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