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# Light-by-light control enabled by incoherent beam superpositions in multimode fibres

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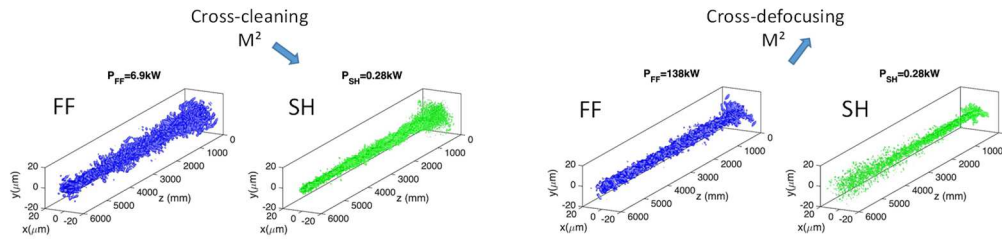
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Multimode fibres (MMFs) have recently demonstrated a great potential towards discovering numerous new and complex processes that have never been observed, so far [1]. Among others, Kerr self-cleaning has unveiled the ability of graded-index (GRIN) fibres to produce a quasi-single-mode beam, despite the incoherent multimode propagation involving a large number of modes [2]. A clean beam with its improved brightness can then be obtained at the output of the GRIN MMFs. This phenomenon is enabled by the combined effect of self-imaging and Kerr nonlinearity, followed by a nonlinear nonreciprocity of the mode coupling process. This high-intensity self-transformation can also be described by a thermodynamic approach, whenever a large number of modes is involved [3-4].

In this paper, we extend the concept of Kerr-induced beam self-cleaning to any beam that can co-propagate with a strong wave in a GRIN MMF. We used a weak visible beam at 515 nm that was superimposed on a strong fundamental pump at 1030 nm. Due to their independent coupling into the optical fiber, the number of excited modes at each wavelength was drastically different. Since optical fibers typically do not feature  $\chi(2)$  nonlinearity, space-time coherence was not possible, as well. Therefore, the propagation of the two beams could be considered as incoherent. Under these conditions, we showed that the  $M^2$  coefficient of the weak beam was improved by increasing the pump power at 1030 nm, due to cross-phase-modulation between the fundamental frequency (FF) and the second harmonic (SH) beams. However, and differently from previous experiments, we also demonstrated that, by further increasing the pump power, the initially observed self-cleaning of the weak beam was changed into a defocused beam, with increased  $M^2$  coefficient, instead. Modal energy distribution in favour of either low-order-modes or high-order-modes could be obtained, depending on the input pump power. Thus, our results uncover a new property of the spatial self-organization effect, which is driven by four-wave-mixing processes, where the phase accumulation through cross-phase-modulation might determine the direction of the energy flow. For enough modes excited, the local phase introduced by the fundamental pump on the weak beam is the result of a superposition of many modes. As a matter of fact, one can even consider an average phase distribution, permitting to apply a calorimetric description of the aforementioned cross-rearrangement of the fundamental beam within a thermodynamic framework [5]. Indeed, the second law of thermodynamics does not prevent the modification of the spatial beam quality, which is associated with the statistical temperature, neither towards its improvement nor its deterioration. As it occurs in a calorimeter, in MMF the temperature of the two beams vary towards an equilibrium value owing to their interaction (exchange of heat). Our findings can be extended to laser sources for an ultrafast control of their operation, opening a new way towards the light-by-light control. Supercontinuum generation in MMFs could also benefit from this new approach, allowing for an ultrabroadband single-mode emission at high powers [6].



**Fig. 1** Examples of cross-cleaning (left) and cross-defocusing (right) of a weak beam by using a strong pump wave at different wavelength in GRIN optical fiber (50/125  $\mu\text{m}$ ,  $L_{\text{fiber}}$  12m).

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