Spatial beam self-cleaning in multimode fibers: the role of light polarization

Mario Ferraro[a], Fabio Mangini[a], Raphaël Jauberteau[a], Mario Zitelli[a], Yifan Sun[a], Pedro Parra-Rivas[a], Katarzyna Krupa[b], Alessandro Tonello[c], Vincent Couderc[c], and Stefan Wabnitz[a,d]

[a]Department of Information Engineering, Electronics and Telecommunications (DIET), Sapienza University of Rome, 00184 Rome, Italy
[b]Institute of Physical Chemistry, Polish Academy of Sciences, Warsaw, Poland
[c]XLIM Institute (UMR CNRS 7252), University of Limoges, 87060 Limoges, France
[d]CNR-INO, Istituto Nazionale di Ottica, Via Campi Flegrei 34, 80078 Pozzuoli, Italy

ABSTRACT

Since its first demonstration, spatial beam self-cleaning has been targeted as a breakthrough nonlinear effect, for its potential of extending to multimode fibers different technologies based on singlemode fibers, such as fiber lasers and endoscopes. To date, most of the theoretical descriptions of beam self-cleaning are based on scalar models. Whereas, in experiments the analysis of the polarization state of self-cleaned beams is often neglected. Here, we fill this gap between theory and experiments, by demonstrating that a self-cleaned beam eventually loses its degree of polarization, as long as linearly polarized light of enough power is injected at the fiber input. Our results are cast in the framework of a thermodynamic description of nonlinear beam propagation in multimode fibers, providing the first experimental proof of the applicability of scalar theories for the description of the spatial beam self-cleaning effect.

Keywords: Kerr effect, Multimode optical fibers, Beam control, Fiber lasers, Beam shaping, Spatial solitons; Polarization effects

1. INTRODUCTION

Spatial beam self-cleaning (BSC) is a nonlinear effect, which consists of the transformation from speckles into a Gaussian-like bell shape of an optical beam that propagates in a graded-index (GRIN) multimode fiber (MMF).[1,2] The possibility of achieving self-cleaned beams at the output of MMFs may find several technological applications. For instance, BSC allowed for the demonstration of high peak power, mode-locked MMF lasers,[3,4] and permitted an improvement of quality and resolution for multiphoton microscopes and endoscopes.[5,6] From a fundamental point of view, a comprehensive theoretical understanding of the physical mechanism leading to BSC is still missing. However, theories based on thermodynamic principles have been recently proposed: in this approach, a self-cleaned beam is seen as a state of thermal equilibrium, which is reached as a consequence of weakly nonlinear beam propagation in a MMF.[7–9] In particular, such theories are based on the conservation laws of the total optical power and the total momentum (both linear and angular) of the beam that propagates in a MMF, along with the maximization of a polarization-independent entropy.

In this context, it is worth noting that most of theoretical descriptions of BSC involve purely scalar models for monochromatic waves, and only a few works consider the state of polarization (SOP) of light.[10,11] Whereas, to the best of our knowledge, only a preliminary experimental study of the SOP dynamics upon nonlinear beam propagation has been reported, so far.[12] In that work, it has been shown that the SOP evolution is rather complex, owing to the multitude of modes involved. In particular, BSC is followed by a reduction of the total degree of polarization (DOP), along with a simultaneous increase of the degree of linear polarization (the input SOP being purely linear). Still, the DOP was found to remain quite high, i.e., around 30% when working with

Send correspondence to S.W., email: stefan.wabnitz@uniroma1.it

500 ps pulses and using an 11 m long GRIN MMF span. Therefore, one may naturally wonder whether and when the theory can be applied to the experimental observations, given that, in principle, the input SOP can be arbitrary.

It is straightforward to understand that a scalar theory strictly holds only in two limit cases, i.e., either when the SOP does not vary during the beam propagation, or whenever the beam completely loses its degree of polarization, regardless of the input SOP. In this work, we experimentally verified the second propagation regime. Indeed, we carried out a comprehensive experimental investigation of the SOP of light at the occurrence of BSC. Our results show that, whenever enough power is provided at the fiber input, a linearly polarized multimode beam almost fully loses its degree of polarization at the fiber output, in analogy with the Kerr-induced depolarization that occurs for singlemode fibers.[13,14] To do so, we employed a longer fiber span and much shorter pulses with respect to the aforementioned work by Krupa *et al.*[12] When this condition is reached, the beam acquires a bell shape along all polarization directions with nearly the same mode content. In this sense, our results provide a definitive validation that the thermodynamic theory apply to the BSC effect, paving the way for further studies involving thermodynamic descriptions of multimode optical systems.

2. EXPERIMENTAL METHODS AND RESULTS

In our experiment, linearly polarized light pulses having a time duration of either 174 fs or 2 ps and a center wavelength of 1030 nm were injected with a repetition rate of 200 kHz into a standard 50/125 GRIN MMF from Thorlabs. We chose a fiber length of 20 m, which is one order of magnitude longer than the typical fiber length that has been used for observing BSC, in order to emphasize the role of depolarization effects. At the fiber input, the laser beam had a nearly Gaussian spatial transverse profile. We paid particular attention to ensuring that the beam was injected without any appreciable tilt angle with respect to the fiber axis. This is a key condition for ensuring the emergence of a bell-shaped beam at the fiber output.[15] In the thermodynamic framework, this ensures that modes associated with opposite topological charges have the same occupancy at thermal equilibrium.[16,17]

At the fiber output, the beam was collimated, and its SOP was characterized by means of a standard polarimetric setup. All the optical components of the latter work within a narrow spectral band. Therefore, we inserted a band pass filter (BPF) right after the fiber output. In this way, we could filter out possible losses of temporal coherence, which might artifact the characterization of the output beam. The results are reported in Fig. 1.

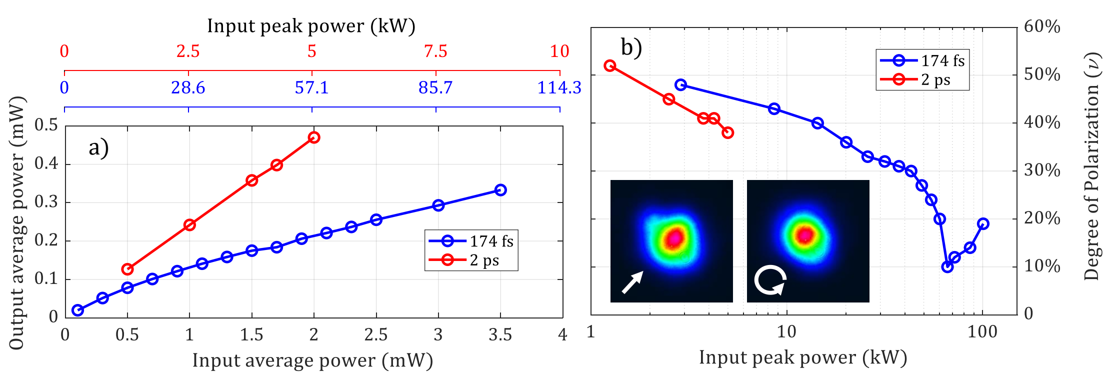

Figure 1. Difference between the BSC of picosecond and femtosecond pulses. (a) Total transmitted power vs. input average power. Horizontal axes on top of the panel show the input peak power corresponding to each pulse duration. (b) Comparison between the input peak power evolution of the output DOP for pulses of either 174 fs or 2 ps. All the experimental points correspond to bell-shaped near-field intensity profile at the fiber output. The insets show the intensity profile of the output beam at the point of the minimum degree of polarization when it is projected onto either linear or circular polarization.

We found several differences between the BSC regimes of femtosecond and picosecond pulses. The first difference can be seen in Fig. 1a, where we report the total power at the fiber output vs. the input average power. In the case of 2 ps pulses, we found a purely linear trend. Whereas when using 174 fs pulses, we obtained a nonlinear transmission curve. This cannot be ascribed to the presence of femtosecond nonlinear losses, which occur at MW peak power levels.[18] The different slope of the two curves is, in fact, due to the combined action of nonlinear spectral broadening effects and of the BPF placed at the fiber output. In this regard we may note that, owing to the different pulse durations, the input peak power (P_p) values are quite different even though the input average power is the same (see the two additional horizontal axes placed on top of Fig. 1a).

In order to emphasize the role of nonlinearity in inducing a light depolarization, in Fig. 1b we plot the total DOP vs. P_p. As it can be seen, both with 174 fs and 2 ps pulses we found that the DOP decreases when P_p grows larger. In the former case, we could increase the value of P_p up to hundreds of kW, without incurring in any fiber damages. On the other hand, with 2 ps pulses we could not push P_p further than a few kW, since we observed a rapid deterioration of the fiber material and, consequently, the spatial beam intensity pattern became unstable. This difference can be ascribed to thermal effects, which may cause irreversible material damages. Remarkably, these effects can be avoided by employing ultra-short pulses,[18,19] thus allowing for the observation of a more pronounced depolarization effect. As mentioned in the introduction, when studying the SOP of light in the process of BSC and using 500 ps pulses with an 11 m long GRIN MMF span, Krupa *et al.* found that the degree of polarization quenched from 50 % in the quasi-linear propagation regime down to around 30 % at the occurrence of BSC.[12] In that work, instead of material damages, the maximum input peak power was limited by the occurrence of stimulated Raman scattering, which hinders the BSC effect. Whereas here we achieved a threefold stronger reduction of the DOP (i.e., an almost full extinction of the DOP), although the DOP at low powers was nearly the same as in Krupa *et al.*[12] We highlight that the peak powers of the femtosecond pulses used here are quite higher than in other experiments on BSC.[1] This is because, except for the early work by Liu *et al.*,[2] the BSC effect is typically achieved by means of longer pulses, i.e., of the order of tens or hundreds of picoseconds.

As a final result, we observed that, whenever the beam has a sufficiently low DOP, the beam intensity had nearly the same spatial profile along all polarization directions. For instance, in the insets of Fig. 1b we show the intensity profile of the output beam at the point of minimum DOP when it is projected onto either linear or circular polarizations. Accordingly, by means of a mode decomposition tool, we found that the mode occupancy distribution along all polarization directions is the same, within the experimental error (not shown here).

3. CONCLUSION

In conclusion, we studied the nonlinear evolution of the SOP of picosecond and femtosecond laser pulses, at the occurrence of the BSC effect in GRIN MMFs. Our results show that, within the standard injection conditions of linear polarized light, the occurrence of the BSC effect is always accompanied by a loss of the DOP. Eventually, this phenomenon leads to a full nonlinear depolarization of light (we found a minimum degree of polarization below 10%). As a consequence, the mode power fraction follows the same equilibrium distribution, i.e., it is associated with the same thermodynamic parameters, along all polarization directions. Our findings undoubtedly demonstrate the validity of scalar models, such as that provided by a thermodynamic approach, for the description of the BSC effect. In this sense, they make MMF a reliable platform for the experimental investigation of the entropy of nonlinear waves, e.g., for carrying out optical calorimetry experiments.[20] In terms of applications, our results will be of interest for the development of high-power MMF-based technologies, such as fiber lasers and multiphoton imaging devices.

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