Efficient modeling of the transverse mode instability using the phase-matched model

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High-energy lasers that employ fiber amplifiers have stimulated increasing interest due to their growing ability to produce high output powers. While multi-kilowatt output powers have been demonstrated, nonlinear effects must be suppressed in order for the growth in output power to continue. The transverse mode instability (TMI) is one of the lowest-order nonlinear effects that limit output power in fiber amplifiers [1–3]. TMI is triggered by a thermally seeded refractive index grating that enables coupling between multiple optical transverse modes due to quantum defect heating. To understand and efficiently suppress TMI, computationally efficient simulation models are required. Coupled-mode equations have been successfully used to model TMI [3]. However, this approach is computationally intensive since the conventional coupled-mode equations that govern TMI are dependent on terms that oscillate on a length scale of the beat length between the fundamental mode and the higher-order modes (HOMs). Hence, computational solution of the coupled-mode equations requires step sizes in the longitudinal direction that are small compared to the beat length. This requirement means that a very fine longitudinal discretization must be used, which comes with a high cost in computation time.

In this paper, we describe the phase-matched model, which is a reduction of the coupled-mode equations, and we demonstrate that it produces a large computational speedup with no loss of accuracy. The phase-matched model disregards the fast-oscillating terms in the coupled-mode equations, which do not contribute to the overall gain due to coupling between the fundamental mode and a single HOM [4]. The phase-matched model only includes terms that make a significant contribution to the coupling between the fundamental mode and the HOM. As a result, we can use a longitudinal discretization in which the spacing is large compared to the beat length. We compare the full coupled-mode model and phase-matched model for TMI with realistic fiber lengths of 10 meters. The phase-matched model yields a computational speedup of two orders of magnitude with no loss of computational accuracy for the cases that we have considered. Using the phase-matched model, we are able to jointly simulate TMI and Brillouin instability, which allows us to determine their interaction and to optimize the fiber geometry, taking into account both effects.

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