Transformation Optics Simulation Method for Stimulated Brillouin Scattering

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Abstract

Stimulated Brillouin scattering (SBS) is a nonlinear phenomenon coupling optical and elastic waves [1]. Traditionally regarded as an undesirable side-effect, it has garnered renewed interest in recent years as a platform for investigating slow light [2], nonreciprocity [3], and for designing high-performance chip-integratable optical elements (laser generators, amplifiers, photonic filters, etc. [1,4,5]). While the design of such devices relies on numerical simulations, frequency-domain full-wave SBS calculations are not readily achievable in COMSOL Multiphysics® software. In this work, we develop a novel approach to enable the simulation of SBS and related phenomena in COMSOL. The method uses transformation optics (TO) [6,7] techniques to implement a time-harmonic coordinate transform that reconciles the different frames of reference used by the electromagnetic and structural mechanics solvers. We show how this strategy can be successfully applied to bulk and guided systems, comparing the results with predictions of established theory [1,8-10].
SBS simulations in COMSOL® software are non-trivial because the electromagnetic and elastodynamic solvers utilize different frames of reference, namely the Eulerian and Lagrangian (or material) frames. The former tracks the movement of all material (or mesh) points by updating their coordinates in time, whereas the latter keeps the coordinates fixed, while assigning to each material (or mesh) point a vectorial displacement. Simply coupling through weak contributions physics nodes cast in these two different frames would neglect the effect of material movement in the electromagnetic solver. To solve this problem, we utilize TO, which is a well-established computational and design method, that in this context is able to mimic the material displacement by a change in the electromagnetic material properties in the Eulerian coordinate system used by the electromagnetics solver. Specifically, we adopt the deformation gradient tensor F (available as a built-in quantity in the Structural Mechanics Module) as a Jacobian for the coordinate transformation used in TO. We can then express a new metric as a function of F, which can then be applied to the electromagnetic material properties. Thus, Maxwell's equations can be recast and we arrive at a modified form of the electromagnetic master equation, which can be implemented into COMSOL® software.
In the attached figures, we show results from the investigation of two different systems. In the first, we study a solid-state bulk medium in which backwards Stokes SBS takes place in an amplifier configuration, as depicted in Figure 1. In Figure 2, we show that results from our method exactly replicate the theoretical predictions [1]. In the second case, we study a 2-D dielectric slab waveguide (Figure 3), in order to demonstrate how significant the effect

of material motion and waveguide thickness are on the SBS gain. Results are presented in Figure 4, and they highlight the entirely different behavior predicted by a computational model that does take into account material and boundary motion.

Reference

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Figures used in the abstract

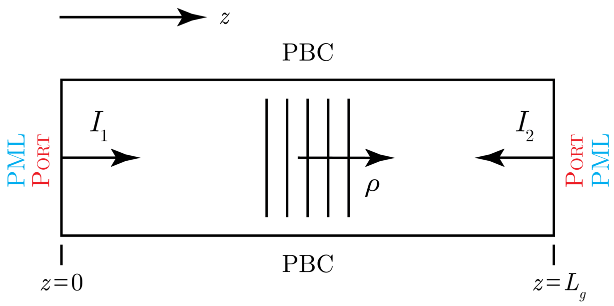

Figure 1: 1-D SBS amplifier: schematic of simulation. Boundary conditions in red refer to optics, in cyan refer to mechanics.

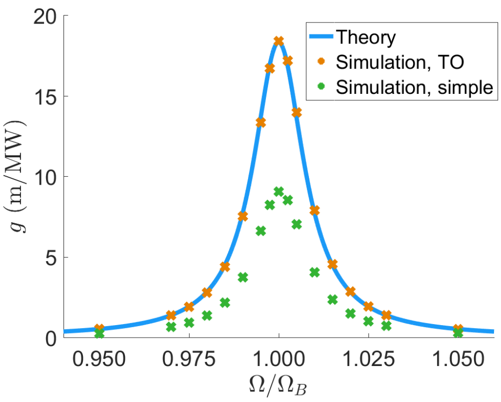

Figure 2: 1-D SBS amplifier: gain spectrum predictions: theory (blue, continuous line) against simulations run with TO method (orange, discrete points) and without it (green, discrete points).

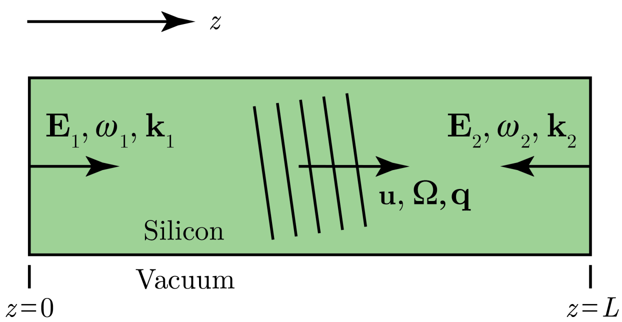

Figure 3: 2-D silicon slab waveguide SBS amplifier: schematic of fields, frequencies, and wavevectors.

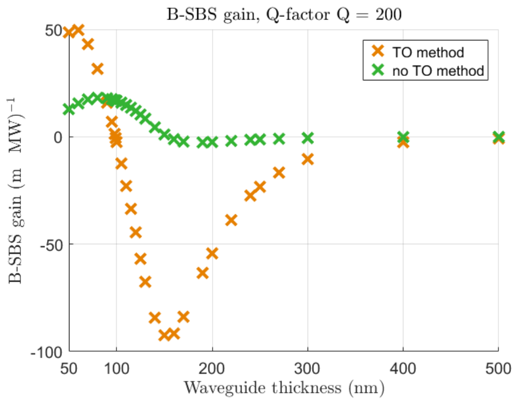

Figure 4: 2-D silicon slab waveguide SBS amplifier: gain as a function of size, with TO method (orange series) and without it (green series).