Brillouin based lasers, nonreciprocity, and cooling in silicon

(Invited paper)

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ABSTRACT

We use a new class of optomechanical waveguides—that produce enhanced light-sound coupling—to realize strong and tailor able stimulated Brillouin scattering interactions silicon photonics. Exploiting these interactions in a variety of different structures, we create high-gain Brillouin amplifiers and integrated Brillouin lasers within a silicon-on-insulator platform. Using a Brillouin active multimode waveguide to realize efficient interband coupling, we also demonstrate a tunable and wideband (>100GHz) nonreciprocal light propagation as the basis for multiport circulator technologies. Leveraging similar concepts in a resonant geometry, we describe a high gain unidirectional amplifier that yields \(\sim 30\)dB of optical isolation. Finally, we demonstrate laser cooling of Brillouin-active phonon modes within guided-wave systems as a means of controlling noise within a broad class of Brillouin technologies.

Keywords: silicon photonics, Brillouin, waveguide, nonlinear optics

1 INTRODUCTION

Both Kerr and Raman nonlinearities are greatly enhanced by tight optical-mode confinement in nanoscale silicon waveguides\([1, 2]\). Counterintuitively, Brillouin nonlinearities—which arise from the coupling between photons and acoustic phonons—are exceedingly weak within these highly nonlinear silicon waveguides. This occurs because material response and poor acoustic confinement within conventional silicon on insulator (SOI) waveguides effectively stifle Brillouin nonlinearities \([3]\). However, new optomechanical waveguides—that control both light and sound—have recently transformed Brillouin interactions into the strongest and most tailorable nonlinearities in silicon \([4, 5, 6, 7, 8]\).

In this paper, we explore the new device physics that enables dramatic enhancement of Brillouin nonlinearities, and we demonstrate a range of highly engineerable new stimulated Brillouin interactions in silicon waveguides by controlling both light and sound. In particular, we describe recent advancements that have yielded high performance Brillouin amplification \([6, 7, 8]\), Brillouin laser oscillators \([9]\), nonreciprocal light propagation \([10]\), and phonon mode cooling techniques in silicon-based Brillouin photonics\([11]\). We also explore future directions and new scientific and technological opportunities offered by silicon-based Brillouin photonics.

2 MAIN TEXT

New waveguide geometries are necessary to produce efficient Brillouin interactions using in silicon photonics. It is perhaps counterintuitive that the same nanoscale silicon-on-insulator waveguides—that greatly enhance Kerr and Raman nonlinearities—effectively stifle the production of Brillouin nonlinearities. This is because the unusual acousto-optic properties of silicon cause light- and sound-fields to couple two transverse elastic wave motion, and the conditions for confinement of sound becomes increasingly stringent at sub-wavelength scales \([3]\). This problem is compounded by the fact that the sound velocity in silicon core exceeds that of the silica cladding, meaning that an SOI waveguide does not produce total internal reflection for sound \([12]\). Consequently, generated sound-fields typically radiate into the substrate of such waveguides \([3]\). This problem has been addressed using new suspended waveguide geometries that use either an air cladding \([4, 5, 6, 7, 8]\) or phononic crystal cladding \([13]\) to reduce or eliminate the leakage of sound waves into the substrate.

As a result of silicon’s unusual acousto-optic properties, these Brillouin-active waveguides produce coupling between co-propagating optical waves through process termed forward stimulated Brillouin scattering (forward-SBS). Because these Brillouin-active silicon waveguides yield distinct dynamics from prior guided-wave systems—which almost exclusively couple counter-propagating optical waves via backwards stimulated Brillouin scattering (backward-SBS)\([14]\)—conventional strategies for Brillouin based signal processing are not always directly applicable using Brillouin processes in silicon. On the other hand, the unique dynamics supported by forward-SBS open door to wideband schemes for nonreciprocal light propagation \([10]\), new laser designs \([9]\), and microwave-photonic signal processing schemes \([13, 15]\) that offer an array of advantages relative to conventional backward-SBS interactions.
Forward-SBS scattering can occur through both intra-modal (intra-band) and inter-modal (inter-band) scattering processes; these two processes good are you know what happened in which have been shown to yield very different dynamics [16], [17], [18]. The first demonstrations of stimulated Brillouin scattering in silicon were made through use of inter-band forward stimulated Brillouin scattering processes within suspended waveguide structures [13]. Subsequent experimental studies improved these results to yield larger nonlinear coefficients [5] and also produce modest (~0.5dB) net amplification [6] by using different structures that more tightly confined the phonons while also reducing optical losses. However, the dimensional sensitivities within these smaller waveguide systems were shown to produce both inhomogeneous broadening [19] and excessive nonlinear absorption [20], complicating the prospect for appreciable net amplification. Robust net amplification (5dB) was subsequently demonstrated using membrane-suspended silicon waveguides having a larger mode area, low (0.15 dB/cm) propagation losses, and higher power handling[7]. Thanks to the low losses, and strong Brillouin nonlinearities provided by the system, it was able to produce net amplification for modest (5 mW) pump powers.

Building on these concepts, we present a new type of multi-mode optomechanical waveguide that produces phonon mediated coupling between optical modes with distinct spatial profiles [8]. This process, termed stimulated inter-modal (inter-band) scattering, produces unusual new nonlinear dynamics in the multimode nature of this interaction lends itself to new strategies to control Brillouin interactions [18]. For example, we use stimulated intermodal scattering to create a new type of silicon Brillouin laser described in Ref. [9]. This system first of a kind silicon Brillouin laser formed by fashioning a Brillouin active silicon waveguide into a race-track resonator that supports low loss guidance of two distinct spatial optical modes. By injecting an optical pump wave into the antisymmetric waveguide resonator mode, we are able to produce Brillouin amplification for the symmetric waveguide mode. We reach the threshold for laser oscillation at modest (11mW) pump powers. Since this system is monolithically integrated, the stability of the Brillouin laser allows us to systematically examine the internal noise characteristics of the system, which exhibits sub-kHz internal line narrowing in an unusual regime of self-oscillation.

Building on these recent works, we use this versatile form of stimulated inter-band coupling to demonstrate a variety of new interactions. Within resonant geometries, we harness this process to create new Brillouin-based optical amplifiers. Using a new 4-port optomechanical waveguide geometry, we also show that such inter-band scattering processes produce nonreciprocal light propagation that offers a promising path towards isolator and circulator technologies [10]. Finally, we use these Brillouin interactions to demonstrate laser-cooling of a continuum of phonon modes [21]. This wavevector-selective phonon cooling method opens the door to the control of dissipation and noise in Brillouin photonics.

Looking beyond these specific applications and demonstrations in silicon photonics, we explore promising new directions for Brillouin based technologies in an array of integrated waveguide systems including chalcogenide[22], [23], [24] and silicaf[25], [26], [27], and silicon nitride platforms[28].

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REFERENCES


