NONLINEAR OPTICS

Enhanced Brillouin amplification in Si

Engineering optical and acoustic modes in membrane silicon waveguides has now been used to demonstrate record high net Brillouin amplification in silicon. This technique enables new possible applications including silicon on-chip Brillouin amplification, Brillouin lasers, and Brillouin devices for signal processing.

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A great deal of work in recent years has focused on optical nonlinearities in nanoscale diffraction-limit-sized waveguides, with a particular focus on silicon and silicon nitride waveguides. In such waveguides, the electromagnetic fields are restricted to small cross-sections, resulting in enhanced field intensities. Nonlinear effects are very strong in such devices. Some mechanisms explored include Kerr effect nonlinearities, Raman scattering, nanomechanical effects, and Brillouin scattering. Possible applications of the nonlinear effects include all-optical switching, optical amplification, narrow-linewidth lasers, and non-reciprocal devices. With regard to Brillouin scattering, key hurdles to achieving high gain and efficiency include mitigating undesired optical nonlinearities (for example, two-photon absorption; TPA), and high optical and acoustic waveguide losses. There are also design trade-offs in the required wavenumber matching between the optical and acoustic propagating modes as well as minimizing loss for both modes simultaneously.

Both Brillouin and Raman processes are based on photon–phonon scattering. In the former case, an acoustic phonon is involved, while in the latter case an optical phonon mediates the process. Acoustic phonons are lower-frequency excitations in which the motion of adjacent crystal nuclei are correlated, while for optical phonons the adjacent crystal nuclei have anti-correlated motion. Lasers and optical amplifiers based on stimulated Raman scattering in silicon photonic waveguides have been demonstrated[1]. Ironically, despite the fact that Brillouin scattering is often considered the strongest optical nonlinearity in fibre systems, it has proved difficult to leverage stimulated Brillouin scattering (SBS) in nanoscale silicon waveguides; in particular, achieving significant net optical gain has remained elusive[2], although it has been achieved in other integrated material platforms[3].

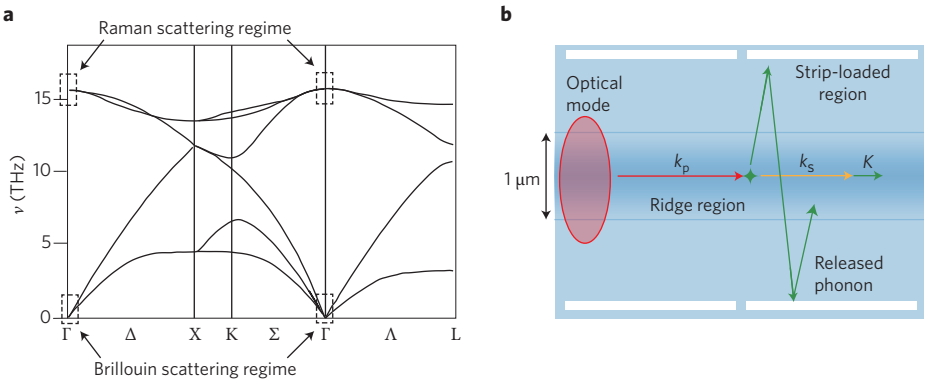

Figure 1 | Phonon mode dispersion for principal points in the Brillouin zone and tethered waveguide device. **a**, Phonons involved in Brillouin and Raman scattering, which are near the Γ point, are illustrated in a phonon dispersion diagram for silicon. The phonon frequency, ν, is plotted against the wavevector in reciprocal lattice vector space and principal directions. Raman scattering typically occurs for phonons near 15.6 THz. **b**, Diagram of device presented by Kittlaus *et al.* Two optical signals, a pump with photonic wavenumber k_p and Stokes wave with photonic wavenumber k_s, of nearly identical energy are involved in amplification based on SBS, in which a phonon is created, and energy is transferred to the Stokes signal from the pump. The optical signal is confined in the central ridge portion. The phonon mode is a lateral standing wave that has a very small forward propagating wavenumber K, for which $k_p = k_s + K$.

Writing in *Nature Photonics*, Eric Kittlaus and colleagues report on SBS in a silicon-based device achieving a large net optical gain of 5.2 dB (ref. 4). Their work makes important advances in several areas. The authors use a membrane version of a new class of structures under investigation by several groups that utilize optomechanical structures to control the interaction between guided phonons and photons. Key advances by Kittlaus *et al.* include independent control in the design and propagation of the optical and phonon modes, allowing loss to be minimized for each, and increased coupling between the two modes. Losses such as TPA and TPA-induced free-carrier loss, and homogeneous broadening in silicon are carefully accounted for in the measurements. The record Brillouin gain is shown to be achieved in the presence of these loss mechanisms in part due to short carrier lifetimes and reduced TPA coefficient compared with nanowire waveguides, another advantage of the membrane approach. Additionally, phonon mode losses are low in the membrane waveguide design.

One of the challenges in using Brillouin scattering is the difficulty of matching the optical wavenumber difference to the wavenumber of the created phonon, while simultaneously conserving energy and allowing low-loss propagation for both the optical and phonon modes. Both Raman and Brillouin scattering share this requirement, but in the case of Raman scattering, the wavenumber-matching constraint is easily met, as shown in Fig. 1. There are a large number of optical phonon modes with near-zero wavenumber values at nearly the same energy level. This is not the case for the acoustic phonons involved in Brillouin scattering. Here, the allowed wavenumber values, at least in a bulk material, have a near-linear relationship to the phonon energy and hence the frequency shift in the scattering process[5]. The phonon

wavenumber for a given frequency shift can be estimated based on the speed of sound in the material; in silicon, for example, the speed of sound is around 8,433 m s^{-1}, hence a Brillouin scattering event involving a photon scattering into a lower frequency with difference of 5 GHz implies a phonon with approximate wavelength 1.7 μm, or wavenumber 3.69 μm^{-1} (ref. 2). But the wavenumber difference between the two photons involved in this process, if the original photon was at 1.5 μm wavelength, would only be on the order of 10^{-4} μm^{-1}.

In addition to the challenge of wavenumber matching, SBS is also significantly weakened at the nanoscale by leakage of phonons into the surrounding material through acoustic coupling[2]. This effect dissipates some of the quasiparticles involved in the coherent process and tends to damp the effect significantly. Another issue has been various sources of nonlinear loss; while the optical intensity inside nanoscale silicon waveguides increases, so can losses to mechanisms such as TPA, making it even more challenging to achieve net amplification. Other losses that must be addressed in silicon or silicon nitride material systems include hydrogen-based material resonant losses (for example, NH bonds) and sidewall scattering loss. The former is typically overcome by designing very-low-height (compared with width), high-aspect-ratio waveguides that were used to demonstrate record low-loss SiN-based waveguides[6].

Several key innovations in recent works have enabled these conventional limitations to be overcome[7,8]. It was observed that the Brillouin scattering could be enhanced in nanoscale waveguides with the proper choice of geometry, based on the interaction between a guided mode and the edge of the waveguide; in particular, radiation pressure, the same effect involved in many nanoelectromechanical systems, can play a large role. Geometries were also developed in which the phonon modes could be dispersion engineered, and the wavenumber-matching conditions met. These modes could also have lower losses due to reduced coupling between phonon modes and the surrounding materials, allowing the phonons to persist longer and thus enhance SBS. Finally, careful design of waveguides and processing choices can result in lower TPA coefficients, and shorter free-carrier lifetimes, also lowering nonlinear loss.

Using a membrane design with low-loss tethered waveguides, Kittlaus *et al.* were able to enhance the Brillouin gain coefficient to the high value of 1,152 W^{-1} m^{-1}. They were able to do so while simultaneously maintaining low optical waveguide losses of 0.2 dB cm^{-1}, and low nonlinear losses as described above. This combination enabled a significant net optical gain of up to 5.2 dB. While small amounts of net Brillouin gain had been previously demonstrated[9], this is the first result approaching the level needed for practical applications such as silicon chip Brillouin amplifiers, lasers and signal processing elements.

Kittlaus *et al.* began with a silicon-on-insulator wafer, similar to many in the field, enabling vertical confinement with a strip-loaded waveguide of an optical mode in the near-infrared regime, in this case using a wavelength near 1.55 μm. They then patterned the top layer of silicon lithographically, followed by an undercut, releasing the silicon to freely vibrate. The lithographic pattern involved a series of fully etched striations in the silicon lateral to the central ridge waveguide, a design approach referred to as tethering. This is a technique typically employed in micro- and nanoelectromechanical systems. A key innovation was the combination of the released geometry with a series of fully etched striations lateral to the central ridge waveguide. Together, this waveguide geometry isolates the optical mode, and creates a tightly confined phonon mode with very low propagating losses and wavenumber, illustrated in Fig. 1. The SBS process involved phonons forming a lateral standing wave, reflecting back and forth off the etched striations in the waveguide strip-loaded region, akin to a lateral Fabry–Perot resonator.

The authors started by characterizing the passive optical performance of their waveguide geometry, and then characterized the nonlinearitites of their system through a series of experiments utilizing continuous-wave optical signals in the 1.55 μm radiation waveband, a standard waveband in telecommunications. The authors measured the Brillouin gain via a small signal pump–probe technique using standard radiofrequency (RF)-swept electro-optic single-sideband modulation. They directed a high power pump signal, and an orders of magnitude lower power probe signal, which they call the Stokes signal, into the device. External modulation using a tunable RF source allowed the pump–probe frequency separation to be precisely controlled. The modulation frequency was used to scan and determine the Brillouin frequency shift Ω at which the amplification occurs. As expected from their theoretical predictions, it was near 4.35 GHz; this frequency corresponds to the phonon mode that laterally vibrates and thus allows the wavenumber-matching condition to be met. By normalizing the known linear coupling and nonlinear losses in the system, Kittlaus *et al.* were able to calculate the net on-chip gain to be 5.2 dB. Further experiments were performed involving two input optical signals of equal power separated by the frequency Ω; the results both confirmed that the Brillouin mechanism was the dominant nonlinear effect, and allowed another measurement of the Brillouin gain coefficient.

One limitation in the SBS results thus far demonstrated is the relatively low frequency shifts, typically on the order of 5–20 GHz. These frequency shifts may be too small for some applications, such as those involving wavelength-division multiplexing,

Table 1 | Typical stimulated Brillouin scattering (SBS) gain coefficients, waveguide losses, and net achieved gain in several situations.

Mechanism	Normalized gain coefficient (g_0/A_{eff})	Linear optical loss	Pump power	Net optical gain demonstrated (dB)	Ref.
SBS in nanoscale silicon waveguide	1,152 W^{-1} m^{-1}	0.18 dB cm^{-1}	62 mW	5.2	4
SBS in nanoscale silicon waveguide	6,561 W^{-1} m^{-1}	5.5 dB cm^{-1}	40 mW	0.5	9
SBS in standard single-mode optical fibre	0.14 W^{-1} m^{-1}	0.2 dB km^{-1}	-	-	10
SBS in As_2S_3 chalcogenide waveguide	310.8 W^{-1} m^{-1}	0.8 dB cm^{-1}	300 mW	10.3	3
Typical III–V semiconductor diode junction	3,000–10,000 m^{-1}	-	600 mW cm^{-1}	-	11

Gain coefficients g_0 are normalized by the effective waveguide area A_{eff}. Also reported is the performance seen in a typical III–V semiconductor gain region for comparison, for which we report a material gain in units of m^{-1} as the mechanism is different. In this case, the power reported is the approximate magnitude of the electrical power dissipated on the junction to achieve the specified gain. '-' indicates data not available.

owing to the fact that distinguishing such closely spaced optical frequencies with passive optical filters is difficult. In this respect, the Raman scattering process has an advantage in that the 15.6 THz shift in silicon corresponds to a broader wavelength shift from, for example, 1.55 μm to 1.686 μm. With further work, perhaps the SBS frequency shifts can be increased. Frequency shifts of 50 GHz would enable more practical passive filtering of the optical signals involved in SBS in a number of platforms.

With this foundational result, it has become possible to engineer efficient SBS in nanoscale silicon waveguides with high enough gain to see use in various applications (see Table 1 for a summary of characteristics and comparison to related works in various systems). For example, we may soon see compact chip-scale Brillouin lasers in this material platform. Owing to the integrated nature of the device and its relatively compact footprint, this approach could eventually be used in large-scale integrated optical systems. What is also exciting about this result is that it has been realized in silicon-on-insulator, one of the world's most commercially accessible material platforms, and without the use of exotic materials or processing steps. It is thus possible that devices similar to these could one day be constructed in complementary metal-oxide–semiconductor (CMOS)-compatible commercial facilities. The work by Kittlaus *et al.* may be a first step towards the utilization of Brillouin processes as an additional tool for on-chip optical nonlinearities and non-reciprocal light flow. ❐

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ORGANIC OPTOELECTRONICS

Stable multilevel memories

Combining a photochromic molecule with a semiconducting polymer yields an organic non-volatile, multilevel memory with a current output that can be switched and controlled by light.

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The fields of organic electronics and optoelectronics[1] exploit thin films made of electroactive and/or photoactive molecular materials to perform various functions. These tasks can include light emission as in the case of organic light-emitting diodes (OLEDs)[2], the conversion of sunlight to electrical energy as in organic photovoltaics (OPVs)[3,4], field-effect current modulation as in organic field-effect transistors (OFETs)[5], and current modulation and light emission in organic light-emitting transistors (OLETs)[6]. Now, writing in *Nature Nanotechnology*, Leydecker *et al.*[7] add to this arsenal with the demonstration of a stable multilevel organic memory device (OMD) that is controlled by light. Once optimized, such an approach could become an alternative to conventional data-storage technologies based on silicon.

The advantages of using organic materials include the promise of low-cost solution processing and the potential for plastic substrate devices that are ultrathin, large area, lightweight, multifunctional and mechanically flexible. Organic optoelectronics has already been successfully integrated in several commercial applications that have become part of our daily lives (for example, OLED-based flat-panel displays). However, the development of robust, high-density OMDs[8,9] is still ongoing.

The purpose of a memory device is to store and access binary digital data in a compact physical element that is coupled to a central processing unit[10]. Electronic memories can be volatile (for example random-access memories, in which the information is lost unless constant power is applied) or non-volatile (for example read-only memories (CDs and DVDs) and flash memories). The key performance parameters in memory devices are cost, speed of data storage and/or transfer, size, power consumption, the device lifetime in terms of the number of rewrite cycles, cycling stability and data retention time. Writing and reading data bits using different physical processes such as light and charge transport can improve device reliability.

For a few decades, scientists have attempted to fabricate stable memories that use light inputs to store information in bistable photochromic materials (which undergo a light-activated reversible change between two states). Leydecker *et al.*[7] have now demonstrated that a marriage of photochromic molecules with organic semiconductors is a potentially winning approach to realize robust, high-density, non-volatile, multilevel organic memories that exhibit high switching ratio, excellent data retention time, high field-effect mobility and low programming voltage.

The underlying idea is to tune the charge transport (and thus flow of electrical current) in a composite organic semiconductor by combining the photoswitching capability of a photochromic molecule with the electroactive properties of another molecule or polymer.

Several materials and device structures with bistable states (a requisite for an OMD) have already been demonstrated[9]. In previous work, an ingenious approach to create phototunable energy levels, thereby forming bistable states, by blending diarylethene (DAE, a small photochromic organic molecule) with the well-known organic semiconducting polymer poly(3-hexylthiophene) (P3HT) was reported[11]. The photochromic molecule (DAE or its