Harnessing On-Chip SBS

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Stimulated Brillouin scattering—a familiar nonlinear effect in macroscopic systems such as fiber optics—is finding new applications in communication, quantum manipulation and microwave filtering in an era of integrated photonics.
Fundamentally, SBS—the strongest of all nonlinear optical processes—is a two-way interaction between sound and light, in which light traveling through a material creates acoustic vibrations within it, which in turn scatter the light. Well-known as a problem to be overcome in long-run optical fiber systems, SBS has also been harnessed more positively in a wide variety of applications in ultra-narrowband lasers, microwave signal processing, and other areas. And, in the new world of integrated photonics in particular, the long coherence time of slow-travelling, gigahertz acoustic phonons can be used to accelerate, slow down, store and frequency-shift optical signals. Harnessing those interactions is creating new approaches to generating high-spectral-purity microwaves and for realizing broadly tunable, narrowband microwave filters.

Controllable, efficient coupling between coherent photons and phonons can greatly enhance the performance and functionality of integrated photonics and optoelectronics. Harnessing SBS in a chip scale device is, however, challenging, with several stringent requirements. First, the photonic structure must exhibit both optical and acoustic guidance. And, second, the material needs to provide sufficiently high Brillouin gain.

This article takes a broad look at the emerging role of SBS as a tool in integrated photonics—and at how that integration might happen, particularly using chalcogenide materials.

The physics of SBS

The notion that optical energy can affect mechanical movement or vibration has been recognized since the 17th century, when Johannes Kepler noted that the dust tails of comets point away from the sun during a comet transit. James Clerk Maxwell later explained this phenomenon: because light carries momentum, optical radiation should give rise to pressure. A few decades after that, in the early 1920s, Leon Brillouin and Leonid Mandelstam independently studied diffraction of light by sound, which led to discovery of the inelastic scattering phenomenon that came to be called Brillouin scattering.

On a quantum level, Brillouin scattering happens when a pump photon, interacting with thermally generated vibrations or phonons in a nonlinear material, is annihilated and converted into an acoustic phonon and a lower-energy (red-shifted) Stokes photon, usually propagating in the opposite direction. Stimulated Brillouin scattering happens when a strong modulated light field itself generates the acoustic vibrations, via electrostriction—the tendency of dielectric materials to deform under an external applied electric field.

In a typical SBS scenario (see figure at right), a pump signal interferes with a counter-propagated probe, or Stokes, signal. If the two signals have the same frequency, their interference forms a standing wave; if their frequencies differ, however, the interference creates a moving “beat” at the frequency difference that compresses the medium through the process of electrostriction. If the beat frequency is close to the material’s acoustic resonance, it creates...
For any new technology, including SBS photonics, integration with other optoelectronic components constitutes a crucial variable.

an acoustic wave. And the process proceeds in a self-sustained loop: SBS generates sound that leads to further scattering, reinforcing the initial beat note.

The first experimental demonstration of SBS dates to 1964, when the creation of ruby lasers finally provided the high-power, coherent light necessary to explore the phenomenon. In the late 1960s, SBS was also demonstrated in liquids and gases. With the advent of low-loss optical fibers in the early 1970s, SBS was observed in a germanium-doped silica fiber at relatively low, sub-watt optical powers, as the fiber core allowed the light to be confined over a long distance.

**Moving SBS to the chip scale**

Conventionally, SBS has been viewed as a bulk effect, with no reference to geometry. But that view breaks down for structures at the nanoscale, where boundary effects can no longer be neglected and where radiation pressure plays an important role in acoustic behavior. The engineering of radiation pressure in micro- and nanoscale systems, such as nanoscale waveguides and resonators, creates opportunities for strong enhancements in phonon-photon interactions.

Taking advantage of those opportunities, however, requires finding the right material. Many material properties—including refractive index, elasticity and acoustic velocity—as well as the acousto-optic confinement play a crucial role in device function and power efficiency. To date, SBS on a chip has been demonstrated using chalcogenide waveguides, silica-on-silicon wedge resonators, calcium fluoride resonators and silicon-on-silicon-nitride integrated platforms. Each solution has advantages and disadvantages, and the search for the ideal photonic platform for sound-light interactions continues.

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>As₂S₃ (guide)</th>
<th>CaF₂</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REFRACTIVE INDEX</strong></td>
<td>1.45</td>
<td>2.45</td>
<td>1.43</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>ACOUSTIC VELOCITY</strong></td>
<td>5,960 m/s</td>
<td>2,500 m/s</td>
<td>6,600 m/s</td>
<td>8,900 m/s</td>
</tr>
<tr>
<td><strong>BRILLOUIN COEFFICIENT</strong></td>
<td>4.52×10⁻¹¹ mW⁻¹</td>
<td>0.74×10⁻¹¹ mW⁻¹</td>
<td>2.8×10⁻¹¹ mW⁻¹</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Comparing opto-acoustic properties

Chalcogenide materials such as As₂S₃, combining low acoustic velocity and high Brillouin coefficient, provide much more efficient photon-phonon interaction than alternatives such as silicon-on-insulator photonic structures.
with a high sound velocity, so acoustic vibrations tend to escape into the cladding or substrate.

One approach to solving that problem is to isolate the silicon waveguide from the substrate for as great a length as possible—or, perhaps more promisingly, to create acoustic resonances within a membrane that suspends the silicon waveguide. A group from Yale University, USA, recently demonstrated this idea with a system in which a silicon nanowire is supported by a silicon nitride membrane, with slits that cause the acoustic waves to be reflected back, thereby creating the resonance.

The chalcogenide alternative

Another solution, of course, is to put less emphasis on CMOS compatibility and look for an alternative nonlinear material platform with better acoustic properties. And here, chalcogenide photonics is providing some interesting possibilities.

A research field that emerged almost two decades ago, chalcogenide photonics explores the unique properties of chalcogenide glasses, and provides a solution for nonlinear signal processing and mid-infrared photonics using chip-scale devices. Chalcogenide glass contains one or more chalcogen elements (S, Se, Te), covalently bonded to network formers such as As, Ge, Sb, Ga, Si or P. These glasses feature high refractive index (2.3 to 2.9), strong Kerr nonlinearity (100 times that of silica glass) and transparency across a broad mid-infrared wavelength range (3 to 10 microns).

Chalcogenide glasses can be deposited on a silicon wafer and processed to form complex circuits of rib waveguides, photonic crystals and ring resonators. Chalcogenide waveguides in particular can show excellent acoustic guidance—with the overlap between optical and acoustic modes close to unity—because the speed of sound in the chalcogenide glass is lower than that in the cladding material, partially composed of silica glass. Together with the high Brillouin gain coefficient, this leads to a very efficient photon-phonon interaction. Overall, the Brillouin gain of a chalcogenide on-chip waveguide is a factor of 500 larger than that of a standard single-mode silica fiber.

The past few years have seen several key demonstrations of signal generation and processing functions, of both applied and fundamental interest, based on SBS in chalcogenides. These include physical phenomena such as cascaded SBS, slow and fast light, and Brillouin dynamic gratings, as well as devices such as

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**High-resolution microwave photonic (MWP) filters.**

On-chip stimulated Brillouin scattering (SBS) offers a route to high-resolution integrated MWP filters. SBS-based on-chip filters have high selectivity, high stop-band rejection, reconfigurable response and ultra-wide frequency tuning. Filters with MHz-scale resolution and beyond 50 dB extinction have been realized. This has made it possible to realize compact, frequency-agile, high-resolution filters, using the novel spectral-shaping technique recently introduced in MWP.

Key applications for such high-quality filters include radio astronomy, wireless and satellite communications, and radar signal processing, where frequency-agile filters are required to reduce the impact of unwanted interference or hostile jammers. D. Marpaung and M. Pagani.

**Frequency combs.**

Gigahertz (GHz) frequency combs are of particular interest, as the distance between the comb teeth corresponds to the bandwidth of modern electronics. Recently, 8 GHz frequency combs have been demonstrated in chalcogenide chips that harness cascaded SBS in a waveguide, assisted by a Bragg grating. T.F.S. Böttner et al. Optica 1, 311 (2014)
single-frequency Brillouin lasers, Brillouin frequency combs, microwave photonic filters and microwave tunable phase-shifters.

The future of SBS photonics

Photonic integration will play a key role in leveraging SBS-based technologies for real-world applications such as sensing and signal processing. Integrating optical waveguides that exhibit efficient SBS, together with critical components such as optical modulators, optical switches, and photodetectors, in a single photonic chip will enhance system stability—for example, thermal stabilization is easier to achieve for devices integrated on a single chip. And such integration also significantly reduces footprint, weight and power consumption.

The route to monolithic integration of these functionalities is challenging, however, since it requires efficient photon-phonon interactions in material platforms that support active elements such as high-speed electro-optic modulation and detection. At present, these platforms are limited to silicon (or to “III-V” materials such as indium phosphide). And although efforts to harness SBS in silicon are gearing up, the achievable gain is still insufficient for many applications.

The second route to integration is the hybrid approach, in which two or more material platforms are combined to achieve optimum operation. For SBS, this can be realized, for example, by combining chalcogenide waveguides, in which SBS is generated, and silicon components to support modulation, detection and switching. Encouraging progress has already been achieved with chalcogenide-silicon hybrids, and with electro-optic LiNbO3 waveguides.

Whether through monolithic or hybrid integration routes, highly integrated, chip-based SBS has strong potential to revolutionize technologies including tunable microwave photonic signal processors, gigahertz-repetition-rate frequency combs, low-noise microwave sources and high-sensitivity sensors. In the integrated photonic chips of the future, light may well be dancing to an acoustic beat, in some interesting and productive ways.

References and Resources