Perspectives on stimulated Brillouin scattering

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Abstract
This collection of papers describes research that goes into detail on some of the more important issues in the physics of stimulated Brillouin scattering. This perspective describes the earliest years of the physics of stimulated Brillouin scattering, along with key developments that have led to this technically and physically rich field of today’s nonlinear optics. Stimulated Brillouin has a profound effect in optical fiber communications, initially discovered by its limit on the transmitted power. By controlling SBS in fibers and making use of its phase conjugation properties in both fibers and bulk media, a wide range of applications have been enabled. Today ring Brillouin lasers in fibers, whispering gallery modes and in photonic integrated circuits provide optical delay lines and switches, pulse shapers and components for increasingly complex and important optical systems.

1. Introduction

Just over fifty years ago Stimulated Brillouin Scattering (SBS) was predicted and observed in the Charles Townes laboratory at MIT. The importance of the phenomenon, both scientifically and in applications, was certainly not appreciated at that time. Since that time, however, extensive research, particularly in the last ten years, has demonstrated the importance of SBS. Figure 1 analyzes the number of research papers per year published under the topic ‘Stimulated Brillouin,’ a total of 4243 papers to date (2465 in the last ten years!). The site lists 49 562 citations to those papers, demonstrating the lasting importance of SBS. In comparison, Google Scholar lists 153 000 sites under the same search term. The research papers in this collection provide specific windows into some important aspects of present-day research in SBS. This author’s perspective is as an involved MIT graduate student from 1964–1966. This contribution is written with a mixture of awe and pride about what has become of that group’s research.

This perspective provides first a brief historical background on the origins of Brillouin scattering and then on the development and demonstration of SBS. It describes how phase conjugation led to phase conjugate mirrors and their applications. Initially SBS in fibers was a curse, but became a blessing when the physics became understood well enough to offer a measure of control to the optical systems. This led to practical research directions such as improvements in laser output (linewidth narrowing and aberration correction), pulse compression, beam combining and phase locking, Brillouin lasers and amplifiers in erbium-doped glass fiber, as well as in traditional bulk lasers and amplifiers. More recently, nanotechnology has led to studies of SBS in nanoscale photonic integrated circuits and photonic crystal fibers, enabling more detailed studies of the interaction of phonons with finite-sized structures and with the light. These topics are subjects of this collection’s papers: Brillouin lasers in erbium-doped glass fibers, hollow-core photonic bandgap fibers, SBS in suspended nanowires, microrod Brillouin lasers, whispering gallery modes in micro-resonators, nanoscale integrated Brillouin waveguides, and phase-locking in cascaded SBS.

2. Historical background

2.1. Spontaneous scattering: Rayleigh, Raman and Brillouin
Elastic scattering of light was introduced by Lord Rayleigh (John Strutt) in order to explain why the sky was blue. He refined his theory of scattering in a series of papers that were issued from 1871 to 1899. Questions of both the
cause of this elastic scattering and the impact of thermal molecular motion on Rayleigh’s scattering remained an issue for physicists.

In 1919, Joseph Larmor pointed out that ‘the molecules of the atmosphere are in thermal motion, with velocities in uncorrelated directions’. He suggested that, due to the Doppler effect, ‘the wave-length of the radiation scattered from them will thus vary within a range of $10^{-6}$ of itself’ [1]. The Indian Professor, CV Raman, noticed this paper and pointed out that ‘the movement of an individual molecule would alter the effective frequency of the radiation, and this has to be taken into account in calculating the effective frequency of the emitted radiation as received by the observer’ [2]. Note that Raman’s 1919 paper contains a hint of Brillouin scattering, although it would not actually be observed until 1930. Both Larmor and Raman understood theoretically that inelastic scattering from molecular motion could have a very small frequency shift, which is one way of looking at Brillouin scattering. The inelastic shifts due to molecular motion were so small as to be unobservable, however, and Raman scattering needed to be observed first.

Raman was a very active researcher. He spent the next ten years studying scattering of light in all sorts of materials. His research culminated in the publication of his important paper in Nature in 1928 describing what became known as the Raman Effect and more recently as Raman Scattering [3]. In this paper he said, among other things:

‘We should expect in the case of ordinary light, two types of scattering, one determined by the normal optical properties of the atoms or molecules, and another representing the effect of their fluctuations from their normal state. We have shown that… the diffuse radiation of the ordinary kind, having the same wavelength as the incident beam, is accompanied by a modified scattered radiation of degraded frequency. … Some sixty different common liquids have been examined in this way, and every one of them showed the effect in greater or less degree’ [3].

He followed this very soon by identifying the new wavelengths in his scattering experiments, concluding, ‘The modified scattered radiation was readily detected by the appearance in the spectrum of the scattered light of radiations absent from the incident light…The scattered radiations … showed some sharp bright lines additional to those present in the incident light, their wavelength being longer’ [4].

He presented his definitive work at the Royal Society of London in January, 1929 [5]. This paper, which (surprisingly) has been cited only 6 times (compared to 591 for [3]), said: ‘Our experiments furnish definite proof … that they may occur also in such complicated systems as the molecules of a vapour or a liquid or even in a complete crystal. … As has been shown in our previous papers, lines must correspond to a characteristic frequency of the molecule. In the following table are exhibited the shifts in wave-number of the different modified lines and the corresponding infrared wavelengths characteristic of the molecule. … Considering the uncertainties in the direct measurement of infra-red spectra, the agreement between the values of the characteristic wave-lengths calculated from light-scattering and those measured directly should be considered satisfactory; thus confirming the conclusions drawn in our previous papers regarding the origin of the modified lines’ [5].

Thus CV Raman introduced the concept that inelastic scattering of light with relatively large frequency shifts could take place in matter, due to interaction with intramolecular vibrations.
Brillouin scattering, on the other hand, is due to interaction with intermolecular vibrations. In solids thermal motion can be characterized by macroscopic vibrations of the material; i.e. acoustic waves (acoustic phonons). Inelastic scattering in solid state matter was proposed based on theoretical grounds by Brillouin in 1922 [6], but experimental work waited until after studies of the Raman effect. In 1930 Brillouin scattering was reported by the Russian Evgenii Fedorovich Gross, published in English in Nature [7], told in his own words here:

'...Soon after the discovery of the Raman effect, I attempted to find out whether in light scattered in various organic liquids the Raman lines, due to frequencies of the rotation spectrum, are present. These lines should be situated very close to the incident line...it was observed that besides the radiation with a wavelength equal to the incident one, there were also other radiations of nearly the same intensity, the wave-lengths of which are symmetrically displaced relatively to the incident wave towards greater as well as smaller wave-lengths by a value depending upon the kind of liquid, but not differing greatly from 0.05 A for all liquids studied.

An explanation of the observed splitting of the scattered light is that this splitting is due to acoustic oscillations. ...These elastic heat waves propagate in the medium with the velocity of sound and produce periodical variation of the amplitude of the scattered light, thus giving rise to two new frequencies:

\[ \nu = \nu_0 \pm \nu_a (\nu/c) \sin(\theta/2) \]  

Here \( \nu_0 \) is the frequency of the incident light, \( \nu \) is the velocity of sound and \( c \) that of light in the medium, and \( \theta \) is the angle between the incident and scattered ray.

'This equation was given by Brillouin (Ann. De Phys., 17, p 88; 1922) and also by Mandelstam (Jour. Russ. Phys.-Chem. Soc., 58, p 831; 1926), who has derived it from somewhat different considerations'.

The acoustic oscillation frequency giving rise to Brillouin scattering is

\[ \Omega = \nu - \nu_0 = \nu_a (\nu/c) \sin(\theta/2), \]

with spontaneous emission typically measured at 90 degrees. Because the velocity of sound (~10^5 cm s^-1) is much smaller than the velocity of light (10^10 cm s^-1), these acoustic waves have hypersonic frequencies on the order of 10^5 Hz.

A modern view that couples Brillouin and Raman scattering is through the acoustic phonon picture of vibrations in matter. Raman scattering corresponds to interaction with the phonon spectrum’s optical branch, while Brillouin scattering corresponds to interaction with the acoustic branch.

After Gross’ paper, he and a few other researchers investigated with more care the structure of the spectrum of ‘Rayleigh Scattering’. That is, the nearly-elastic scattering of incident light when transmitted through a medium. The researchers were trying to explain the homogenous broadening that was typically observed in gases. Research was hampered by the lack of equipment to measure very small frequency shifts; it would take until the late 1950’s for proper equipment to become available.

3. Spontaneous Brillouin scattering in modern times

In 1957 D H Rank at Pennsylvania State University introduced the use of a narrow-band single-isotope mercury lamp and interferometric techniques to obtain the resolution necessary to measure relative intensities of the Rayleigh and Brillouin scattering in liquids, in order to validate theory [8]. In 1959, Boris Stoicheff from the National Research Council in Canada, presented a paper at the Ohio State University International Symposium on Molecular Spectroscopy, showing measurements of Brillouin Spectra in vitreous silica taken with a high resolution, 35 ft. grating. The acoustic velocities they determined from the Brillouin scattering formula were in excellent agreement with the values determined by acoustic methods.

3.1. Stimulated scattering processes

Soon after the very powerful ruby laser was demonstrated in 1960, the stimulated analog of these scattering processes became observable. Stimulated Raman scattering (SRS) was observed as a result of building the first Q-switched laser. This author was a graduate student in the laboratory of Professor Charles Townes at MIT.
when SRS was first observed. Through developing an understanding of SRS, we realized that the generation of coherent molecular vibrations in SRS led to the prediction of generating coherent phonons. Dr Townes presented our theory, along with its predicted threshold, at the Enrico Fermi Summer School at Verona, Italy in the summer of 1963 [9], then we demonstrated experimentally the first instance of stimulated Brillouin scattering. The interesting beginnings of SBS are told here.

3.2. Stimulated Raman scattering
High enough intensity to observe stimulated scattering processes required first the invention of the ruby laser Q-switch. This technique was suggested and demonstrated by Robert Hellwarth and collaborators at Hughes Research Laboratories in 1962. They inserted an electrically-switched nitrobenzene Kerr cell modulator inside a ruby laser cavity [10] to form ~10 nsec pulses. When E J Woodbury and W K Ng experimented with this laser, they discovered a new frequency coming out of the laser cavity and tentatively assigned it to a ‘new wavelength of ruby’ [11]. Experiments using a different Q-switch and placing a cell of organic liquids outside the cavity determined that this wavelength was a Raman shift away from the ruby laser line. They experimentally demonstrated that they could create Raman-shifted lines in a wide variety of organic liquids [12]. Theory by Hellwarth [13] explained, ‘The Raman process consists of annihilating a photon from a radiation mode and creating a photon in another mode of different frequency, the energy difference being taken up by a transition in the scattering matter from a state i to a state j’. He developed ‘A phenomenological theory to describe stimulated Raman scattering in terms of … ordinary Raman scattering cross sections. This treatment will be analogous to the treatment of ordinary lasers on the basis of absorption and fluorescence data. … Relations which describe the gain that is produced by the stimulated Raman scattering of intense light in a Raman-active material are developed entirely in terms of measurable material parameters. It is this gain which must overcome propagation losses in order to achieve the laser action that has been observed from this effect’.

The Hughes group observed stimulated Stokes radiation, the terminology for the inelastic scattering process that introduces excitation into the medium and stimulates scattered light of smaller photon energy than the incident light. While the scattered Stokes light could be emitted in all directions, the strongest gain was in the forward direction, where the overlap was strongest between the Stokes and incident light beams.

In experimental studies that followed, stimulated anti-Stokes scattering was observed, with a larger photon energy than the incident light. Professor Townes, who was to receive the Nobel Prize for his introduction of the quantum electronics concepts that led to the laser, had become interested in SRS when he heard a talk at the American Physical Society by R W Terhune from the Ford Motor Company [14], which was independently confirmed by Boris Stoicheff, from Canada’s National Research Council [private communication]. They reported experimental results that the Q-switched ruby laser caused SRS in organic liquids with several orders of Stokes radiation and several orders of anti-Stokes radiation. The Stokes SRS was emitted in diffuse directions that were predominantly in the forward direction, but the anti-Stokes SRS emission was into cones whose axis was along the direction of the incident beam.

Discussion at MIT about the many orders of stimulated Raman scattering led us to see that the coherent laser light was able to drive coherent molecular vibrations that would, in sequence, modulate the incident light, providing it with the photon energy to become anti-Stokes [15]. The realization that coherent vibrations existed in the Raman-active media was an important first step leading to the realization of stimulated Brillouin Scattering. From the quantum mechanical view, the coherent vibrations within the molecules could be considered optical phonons. The phonon picture, explained to Professor Townes by Herbert Zeiger, led to the realization that, while coherent optical phonons would stimulate Raman Scattering, there could also be laser-stimulated acoustic phonons that would scatter light shifted by the acoustic frequency: Stimulated Brillouin Scattering.

3.3. Stimulated Brillouin scattering
Professor Townes described the relation we had developed between stimulated Raman scattering and stimulated Brillouin scattering at the Enrico Fermi International School of Physics (1963). He reported our predictions of Brillouin gain due to electro-striction as

\[
\frac{E_0^2}{8\pi} \geq \frac{2B}{(\rho d\varepsilon / d\rho)^2 k_s L \cdot \theta L_{\perp}},
\]

where \(\varepsilon\) is the dielectric constant, \(B\) is the bulk modulus, \(\rho\) is the material density, \(k_s\) and \(k_{\perp}\) are wave vectors of the sound and Stokes light waves, respectively, \(L_s\) and \(L_{\perp}\) are the respective decay lengths. For \(L_s \approx 10^{-2} \text{ cm}\), \(L_{\perp} = 100 \text{ cm}\), and for normal bulk moduli, the power flow to meet the threshold condition for amplification was predicted to be about 1 MW cm\(^{-2}\) [9]. The Brillouin light was assumed to travel in the backwards direction, where the incident and scattered beams overlapped the most, creating the greatest gain.
Experimental demonstration of SBS was first achieved in quartz and sapphire [16]. Because of the small frequency offset, measurements were made in Fabry–Perot interferograms with 3.15 cm$^{-1}$ inter-order spacing. The laser beam had a broad single mode and the results were just as expected: the retro-reflected beam showed a Brillouin shift in crystal quartz of $\sim 1$ cm$^{-1}$, corresponding to $3 \times 10^{10}$ Hz. Measurements of Brillouin shifts for different crystalline directions and for sapphire all agreed reasonably well with predictions.

As a graduate student, the author had focused on investigating nonlinear optical processes in liquids. This unwittingly led to unexplained phenomena in both SRS (later shown to be due to self-focusing) and SBS. The Fabry–Perot interferograms from SBS experiments showed strikingly unexpected results. Figure 2 shows a typical example, the stimulated Brillouin spectrum in water. The left-hand side shows the incident single mode ruby light below threshold for SBS. The right-hand side shows the light coming from the laser above the SBS threshold. Meanwhile the SBS retro-reflected light was too weak to easily measure. What was going on? We came to realize that the Stokes component was, indeed, retro-reflected back into the laser cavity. However, because the ruby crystal was inhomogeneously broadened, the different Stokes wavelength would see non-saturated gain within the laser cavity and be amplified. Upon emergence from the laser cavity, this amplified Stokes wave would re-enter the water at its new, lower frequency. In the water this Stokes-shifted wave would also experience SBS, and be retro-reflected, now at frequency lower by two times the Stokes shift from the incident wave. This explained the results seen in figure 2 where two orders of Brillouin shifts are easily observed [17].

In the following years, research blossomed in three directions: (a) analysis of the hypersonic velocities predicted by SBS and its use to measure material properties; (b) efforts to separate out the amplification in the laser cavity that effected the measurements; time-resolved measurements proved the hypothesis that the author made during her graduate days; (c) research to separate SRS from SBS and self-focusing [18], all of which could occur simultaneously.

The rest of this perspective focuses on highlights of early research toward the impacts of SBS that are most important today.

### 4. Early SBS developments

The earliest years of SBS R&D focused on limitations SBS introduced to practical systems—most notably in fiber optic systems, specifically those designed for telecommunications. At the same time, basic research was underway on SBS gain, along with its possibilities for practical amplifiers. The third direction was providing feedback to create Brillouin lasers, in such geometries as fiber ring and whispering gallery mode lasers.

#### 4.1. SBS in fibers

As soon as optical fibers were developed, it was realized that their optical confinement enabled nonlinear effects to be observed at much lower power levels than in diffraction-limited experiments. Also, the long interaction lengths in fibers could create new dynamic behaviors. In optical fiber communication systems, it was realized
almost immediately that the retro-reflection occurring in SBS would be an ultimate limit to the power levels that could be transmitted through fibers.

In 1972, theoretical analysis by R G Smith from Bell Laboratories predicted that SBS would limit power-transmittal through fibers (while SRS would not be important until the power was 100 times larger) [18]. His study assumed the Nd:YAG wavelength of 1.06 \( \mu m \) (which was 1970’s plans for a fiber communications laser). The paper’s abstract explains his results:

‘The effect of stimulated Raman and Brillouin scattering on the power handling capacity of optical fibers is considered and found to be important especially when low loss optical fibers are used. A critical power below which stimulated effects may be neglected is defined for forward and backward Raman scattering and for backward Brillouin scattering. This critical power is determined by the effective core area \( A \), the small signal attenuation constant of the fiber \( \alpha \), and the gain coefficient for the stimulated scattering process \( \gamma_o \), by the approximate relation

\[
P_{crit} \sim 20 A \alpha / \gamma_o.
\]

For a fiber with 20 dB km\(^{-1}\) attenuation and an area of 10\(^{-7}\) cm\(^2\),

\[
P_{crit} \sim 35 \text{ mW}
\]

for stimulated Brillouin scattering. For stimulated Raman scattering \( P_{crit} \) is approximately two orders of magnitude higher. It is concluded that these effects must be considered in the design of optical communication systems using low loss fibers’ [20].

The same year saw the first experimental report of SBS in fibers, along with the demonstration that it would, indeed, limit power transfer down fibers [19]. Ippen and Stolen used a pulsed Xenon laser at a 0.54 \( \mu m \) wavelength and observed SBS at a threshold input power of less than 1 W in low-loss glass fiber. Extrapolating their data to predictions for a Nd:YAG laser, their results were consistent with a 40 mW threshold. To observe SBS at a threshold below stimulated Raman scattering, they found that the pump laser linewidth must be narrower than the SBS frequency shift.

Thus began a period of intense research to see how the limits given by SBS could be overcome in fiber communications. When laser diodes became the source for fiber optic communications, suitable design for long-distance communications required broadening the laser linewidth to stay below the SBS threshold. Such research considered SBS a detriment, something to get rid of, and so will not be described here.

At the same time, however, SBS was slowly developing valuable practical applications.

### 4.2. Amplification in SBS

Measurements of SBS gain would help researchers both understand SBS and assist designers of applications, initially for amplifiers. As early as 1968, Pohl et al measured transient and steady-state behavior of SBS amplifiers in carbon disulfide in the regime of linear amplification; gain and phonon lifetimes were determined [20].

Fiber optical communication systems found that Brillouin gain could be very useful to amplify weak signals inside an optical fiber. In this case the ‘pump’ would be light inserted backwards into the fiber. If the wavelengths are properly matched, SBS from this ‘pump’ will create gain for the input signal, as [21] explains:

‘Stimulated Brillouin scattering (SBS) in optical fibres is a highly efficient nonlinear amplification mechanism with which large gains have been demonstrated using pump powers of only a few milliwatts. The Brillouin linewidth is only about 15 MHz at 1.5 \( \mu m \) wavelength and this strictly limits the bandwidth of data signals that can be amplified in a fibre Brillouin amplifier (FBA). However, the intrinsic Brillouin linewidth is generally enhanced by compositional inhomogeneities in the fibre and can be intentionally extended by more than one order of magnitude by applying frequency modulation to the pump laser. Moreover, the limited SBS bandwidth has led to one of these amplifiers being used as a narrowband tunable filter and simultaneously to demodulate, amplify and select channels in WDM systems’ [21].

By 1994 many possible applications had been demonstrated, and since then the designs and performance have continued to improve. This collection contains an up-to-date study of one important example, the multi-wavelength-Brillouin–erbium fiber laser (MWBEFL), investigated by Victor Lambin Iezzi and others.

A very different example demonstrates the wide-ranging applications of SBS: all-fiber millimeter-wave generation [22]. The system began by using an optical modulator to generate sidebands on a CW laser and then, ‘two of these sidebands will be amplified by SBS in an optical fiber, whereas the rest will be attenuated due to the natural attenuation in the fiber. The two amplified sidebands are then superimposed in a photodiode. Due to the fact that both sidebands come from the same source, there will be no problem with a phase noise. Furthermore, the system inherent amplification produces very strong sidebands that can be propagated over large distances. A frequency tuning and a modulation of the mm-wave can be done quite simply. … We present the result of phase
noise measurements, which shows that although SBS was used as the amplification process, the phase noise is astonishingly small.

Making use of Brillouin amplification required knowing the Brillouin gain spectrum in single-mode optical fibers, which was carefully measured in 1997 [23]. Half of the growth of publications in the 1990’s, seen in figure 1, is due to research in SBS in fibers; a third is due to laser improvements using Brillouin mirrors (due to phase conjugation, see below), and most of the rest is due to SBS used to study plasmas.

Once amplifiers were understood, it was straight-forward to consider creating a Brillouin laser by providing feedback to the SBS Stokes light amplifier.

4.3. Brillouin lasers

In optical fibers, a simple way to provide optical feedback is by using a fiber ring. The first Brillouin laser, in 1972, was, in fact, a glass fiber ring [24] pumped by an argon laser with an internal etalon to ensure a single longitudinal mode (25 MHz linewidth). It provided a Brillouin laser output power up to 750 mW. By 1982, researchers at Stanford demonstrated a glass Brillouin ring laser with a sub-mW threshold, using a HeNe laser as pump [25].

By the 1990’s, glass fiber Brillouin ring lasers became a popular subject of study, in large part because they could have a very narrow linewidth. In 1991 at MIT, Ezekiel and collaborators demonstrated a Brillouin ring laser pumped by HeNe laser light that had a short-term spectral width of 2 kHz and an intrinsic linewidth of less than 30 Hz [26]. Suggested applications at that time included laser linewidth narrowing, microwave frequency generation, high-rate amplitude modulation, and optical inertial rotation sensing. Pumping these Brillouin ring lasers with laser diodes [27] made them even more practical.

In 2009, an important class of much smaller Brillouin lasers introduced whispering gallery modes for the ring resonator. Both the pump and Stokes waves must be at resonance wavelengths for the ring laser. If the phonon lifetime of the Brillouin-generated phonons is much less than the round-trip time for hypersound in the cavity, standing acoustic waves are not formed and acoustic resonance is not required. This was shown to be true in millimeter-sized resonators [28]. A threshold of 3 μW was demonstrated using a pump of 1 μm Nd:YAG laser light in an ultrahigh Q (∼10^12) calcium fluoride resonator with an angle-polished fiber coupler.

At the same time, researchers at the University of Michigan [29] reported a much smaller whispering gallery sphere (100 μm diameter) that was able to resonate both optical and mechanical waves via compressive radiation pressure. Stimulated Brillouin scattering took place through this interaction, generating both Stokes and a standing hypersonic wave with a frequency of 11 GHz from a pump wave with a free-space wavelength of 1.5 μm. This was the first mechanical resonance enhancement by acoustical recirculation, with an estimated mechanical quality factor of 770, and a concomitant reduction of SBS laser threshold by a factor of 2.3. Their resonator sphere was fabricated from a silica fiber via CO₂ laser reflow.

Recent years have seen a rapid development of photonics, motivated by the possibility of integrating active elements on-chip. Advances in fabrication equipment have enabled smaller and higher quality devices than had been possible in the early days of integrated optics. Brillouin ring lasers have shown considerable promise for practical applications in photonic integrated circuits (PIC’s). Because channel glass waveguides have small electrostriction (meaning a high threshold for Brillouin gain), the first devices were built in chalcogenide waveguides [30]. Silicon has been the substrate most often used in PIC’s, but unfortunately it also has small electrostriction. This difficulty was overcome in 2012 by means of a very high Q silica—on—silicon waveguide ring resonator with a Q of nearly 1 billion [31]. This ring resonator disk had a diameter of approximately 6.02 mm and it was excited by a tunable 1.55 μm wavelength CW diode laser, which was amplified through an EDFA and coupled into the disk resonator using the taper—fiber technique. This PIC technology has opened up a wide range of possible applications in silicon.

This collection contains several papers that illustrate the exciting opportunities lying at the nexus of SBS and nanoscale structures. Brillouin lasers in a microrod resonator, discussed by William Loh, and SBS in whispering gallery micro-resonators, studied by Sturman and Breunig, are two examples of new geometries being considered. Also included are investigations of fabrication and design issues for relevant nanoscale materials. C Wolff analyzes the impact of structural variations in nanoscale waveguides, while Laude and Beugnot study Brillouin scattering and nanoscale electrostriction. Raphaël Van Laer describes a new technique for creating Brillouin lasers in silicon by suspending silicon nanowires to sharpen the phonon spectrum.

5. Phase reversal and phase-conjugate mirrors in stimulated Brillouin scattering

SBS mirrors were found to be extraordinarily valuable in 1972, when Boris Zeldovich and coworkers in Russia realized that the wave fronts reflected in SBS undergo a reversal of their phase [32]. Their argument was based on the fact that stimulated Brillouin gain depends only on the laser intensity, and not its phase, so that the reversed beam grows exactly backwards from the forward-going pump beam. The phase in the Brillouin signal is
therefore the conjugate of the phase in the laser. Zeldovich provided a simple derivation and then proved this analysis is valid for beams that travel at any angle to the z axis.

His paper provided me, for the first time, an explanation for the results of SBS in liquids that I had performed as a graduate student: the SBS went backward through the focusing lens and into the ruby laser where it was amplified. Why could this happen? Because the retro-reflected Stokes beam had its phase conjugated so it followed exactly the path of the incident laser beam.

Understanding the importance of phase conjugation in SBS mirrors was key to a wide variety of studies and applications that followed Zeldovich’s revelation. This collection contains both an article by Buttner et al that makes use of phase-conjugation in their cascaded SBS and the article by Iezzi et al that investigates a multi-wavelength laser enabled by phase conjugation.

5.1. Phase-conjugate SBS mirrors to clean up laser output
Zeldovich’s initial 1972 experiment demonstrated that Brillouin phase-conjugation could remove aberrations from a laser beam. Soon phase-conjugation by SBS was demonstrated in liquids (carbon disulfide), gases (krypton fluoride and HF) and in plasmas. It was realized that, since a phase conjugate mirror corrects wavefront aberrations, it can compensate for distortions of the laser beam created by inhomogeneities in the laser medium and any optical components. The SBS phase conjugate mirror was the simplest way to create phase conjugation and was suitable for high power/energy laser systems. As one example, in 1984 phase conjugation via SBS in methane was used to correct amplifier aberrations in a Nd: YAG oscillator/amplifier system [33]. Some of today’s commercial high power laser systems use SBS mirrors.

In 1992 Andreev et al presented a review of applications of phase-conjugate SRS mirrors that included (1) phase-conjugate mirrors for diffraction-limited beams when the initial laser contains aberration and polarization distortions, especially useful in high power solid state lasers; (2) greater energy extraction when an SBS mirror selectively reflects a coherent signal, but transmits amplified spontaneous emission noise out of the system; (3) laser beam cleanup from coherent speckles or inhomogeneous noise using threshold dependence of the Brillouin mirror reflectivity; (4) coherent coupling of radiation amplified in different optical channels by providing phase conjugation of several light beams with independent phases; (5) pulse compression, because reflection and gain shorten pulses, resulting in higher peak power; (6) pulse shape control using amplifiers and phase-conjugate mirrors pumped by time-shifted auxiliary laser pulses [34].

Since the backward-going Brillouin Stokes has a much smoother spatial beam profile than the incident laser beam, it may sometimes be practical to use the retro-reflected Stokes beam as the output rather than the original laser beam. This is especially true in multi-mode fiber lasers. At Lawrence Livermore, a 150 W near-diffraction-limited pulsed laser-amplifier system was built with SBS wave-front correction for use as a laser guide-star in astronomy [35].

5.2. Beam combining
It soon became clear that phase conjugate mirrors (PCM) were one way to phase-lock and combine several lasers in order to achieve high powers. Brillouin mirrors were held out as a possibility for improved laser fusion drivers, lidar, and other high power laser applications. However, there were several issues that had to be overcome. Since the SBS Stokes output is generated by amplification of thermal noise, its phase has no temporal reference (in conventional SBS configurations). Consequently, if the multiple beams are conjugated by SBS in separate interaction volumes, the Stokes returns will have phase differences which are random and not related to the phase difference of the pump beams. Phase locking is required for separate multiple beams to be coherently combined into a single large-aperture beam with uniform phase front. It is also true that if the initial pump laser is not completely polarized, the polarization state is not restored in SBS. This has required increasingly complex laser systems.

In one example of beam combining with PCMs, researchers at Hughes Research Laboratories built a phase-conjugate master-oscillator power-amplifier in which as many as eight parallel flashlamp-pumped GSGG crystals doped with chromium and neodymium as amplifiers and four parallel frequency doubling crystals were coherently combined for efficient frequency-doubling. They demonstrated an output energy of 8.2 J at 1 μm wavelength (1 Hz repetition rate) with a beam quality only 2.5 times diffraction limit, enabling a 54% frequency-doubling efficiency [36].

The SBS techniques for laser beam combining for high-power, high-radiance sources are now used commonly in commercial systems. Korean researchers have been working for over ten years on developing practical SBS systems for combining lasers to reach the highest powers [37]. Articles from a conference in Asia devoted to SBS and phase conjugation was published five years ago in the journal Laser and Particle Beams [38]. It is a place to realize the vast impact of Zeldovich’s discovery of phase conjugation in SBS.
6. Temporal effects in SBS

This collection contains a paper that deals with temporal effects in SBS, specifically cavity solitons within a Brillouin fiber ring. This is one of the special temporal effects seen in SBS, the first of which was pulse compression. More recently SBS rings have been shown to offer variable pulse delays. Complex optical systems containing two or more SBS rings can be designed to control pulse shapes.

6.1. Pulse compression

It was realized in 1980 that because of the distributed nature of SBS retro-reflection, under certain circumstances the SBS pulses would have a different shape from the incident laser pump. Pulse compression was observed in a tapered waveguide by D T Hon at Hughes Research Laboratories [39]. To quote from his paper,

'We have recently demonstrated controlled pulse compression by SBS with high energy efficiencies. The compressed pulse is wave-front reversed (spatially phase conjugated) while the polarization state behaves like a mirror reflection. These facts combine to make this technique potentially extremely useful for compressing (solid state) laser pulses to the 1 nsec regime. In our experiment, a 200 mJ, 20 nsec pulse from a single-longitudinal-mode Nd:YAG laser is directed into a glass tube placed inside a methane (CH₄) cell pressurized to 130 atm. … The SBS pulse is measured to have a sharp leading spike of 2 ± 0.5 nsec, followed by a smooth tail that resembles the trailing half of the input pulse. … This partially compressed, phase-conjugated pulse was allowed to return to the laser, where a second pulse is generated. This pulse is compressed a second time by the same tapered tube to obtain a 2 ± 0.5 nsec pulse' [39].

This technique of pulse compression has proven important for compressing Q-switched solid-state laser pulses from 10 to 50 times, reducing their width to less than one nanosecond and increasing their peak power by as much as 50 times. Pulses as short as 300 ps and >1 gigawatt peak power have been compressed from a Nd:YAG laser with pulsewidth 16 ns [40]. Their compression ratio of 48 means an increased instantaneous power of the laser by a factor of 48.

6.2. Quasi-solitons

Twenty-five years ago, the dependence of SBS on the shape of the input pulse had already been demonstrated in France [41]. Picholle and co-workers realized that SBS had most often been described as a nonlinear susceptibility process by means of an intensity model, so phase dynamics became irrelevant. This approach is legitimate as long as the inertia of the acoustic wave can be ignored, due to its short spontaneous decay time. They undertook a more rigorous analysis when electrostriction resonantly couples the two electromagnetic waves and an acoustic wave. They found some new SBS dynamics in a ring-cavity fiber laser experiment and were able to stabilize a pulsed SBS Stokes pulse by periodically modulating the CW pump beam with an intra-ring-cavity acousto-optic modulator (AOM). They concluded that dissipative superluminous quasi-solitons could explain the nonstationary dynamic behaviors they observed for the first time in a Brillouin optical-fiber ring laser. The soliton’s contribution to the stabilization of the Stokes output was demonstrated as well as its physical relevance for a self-induced transparency effect on the transmitted pump wave. This is some of the foundational work that inspired the Erkintalo et al paper in this collection.

6.3. Pulse delays

Stimulated Brillouin scattering can be used to introduce variable pulse delays, an ability that could have diverse applications in optical communications. This is done through the ability of stimulated Brillouin gain to alter the dispersion in an optical fiber, by introducing a variable refractive index and changing the group delay of the pulse. Experiments were first carried out in Switzerland, reporting changes in the group index of 10⁻³ over several kilometer-length fibers; pulses were delayed or advanced by nanoseconds [42]. The induced delay depends on the wavelength of a CW pump laser that counter-propagates through the fiber, when the pulses to be delayed are at the Stokes frequency. The delay is largest when the frequency difference between the pump and Stokes waves is at the frequency of the Brillouin-induced hypersonic acoustic wave. The light source was a DFB laser diode operating at 1552 nm with its output modulated to create two first-order sidebands. With the carrier wave suppressed, the frequency difference between the two sidebands was set to the Brillouin frequency shift of the fiber. The upper sideband was used as a CW Brillouin pump, after being amplitude-controlled by an EDFA and a variable attenuator. The lower sideband was reflected by a narrow-band fiber Bragg grating and optically gated to become the probe pulse (the Stokes wave). The time delay of the Stokes pulse was measured for different Brillouin gain by varying the pump amplitude, up to several tens of mW. The input pulse was 100 ns and pulse
delays as long as 30 ns were measured. The same authors later published several ways to improve the delay and make it more practical. They demonstrated a tenfold increase in the available bandwidth by broadening the pump spectrum, thereby expecting that SBS pulse delay technology could operate at telecommunication data rates (up to tens of Gbit s\(^{-1}\)) [43].

At roughly the same time (independently, but 2½ months later) the same idea was introduced by Gaeta’s group at Cornell University [44]. They achieved very similar results with 63 ns pulses, observing 25 ns delay by adjusting the intensity of the pump field and suggested that the technique could be applied to pulses as short as 15 ns, limited by the bandwidth of the Brillouin resonance.

7. Conclusions

The field of SBS, particularly in fibers, is considerably larger than what has been included in this collection of papers. The most important application not discussed here is distributed fiber optic sensors based on SBS. This process has the advantage of automatically sending back information to the origin from anywhere along a fiber. The information carried in the Stokes wave can be anything that will have affected the refractive index or loss of the fiber during the process: temperature, pressure, bends, chemicals, etc. These fibers may be strung out to great distances, or shaped into rings to sense inertial rotation, for example. Spontaneous Brillouin scattering builds up a backward wave whose time-dependence translates into the distance where the phenomenon is taking place. Spontaneous Brillouin scattering has become a really practical technology, although the fiber length is limited by optical losses. Stimulated Brillouin scattering enables the sensor to operate over much longer distances. A distributed Brillouin amplifier increases the pump pulse power along its propagation through the fiber. This technique requires lower pump power than a sensor based on Raman scattering because SBS is intrinsically much more efficient than SRS, with just milliwatts of pump power required to obtain large gain in typical lengths of fiber. Furthermore, the Brillouin gain bandwidth can be electronically controlled to precisely fit the pulse spectrum. The process adds negligible noise to the signal, due to the inherent directionality of Brillouin gain. It only requires incorporating an additional laser whose output is coupled into the sensing fiber, and a signal generator to wavelength-modulate the laser and synchronize the pump pulses [45].

Photonic integrated circuits are finding applications both in communications and as sensors. In this new world of the ‘internet of things,’ sensors will be everywhere and connected back to the internet. In complex high-speed communications systems, optical chips that can carry out needed signal processing are becoming increasingly needed. One example where SBS has demonstrated important applications is in delaying pulses a required amount so that optical signal routing can take place. Another is optical switching at picosecond time scales in micro- or nano-scale rings using SBS created by low-power pumps, or providing GHz-wide optically reconfigurable filters.

Every aspect of nonlinear device/systems behavior, such as SBS, requires us to understand the basic physics, not only of the original process, but of new concepts and processes that provide a wide measure of control, for both the light and the acoustic phonons. When we can control SBS as we like, we have provided another tool in technology’s chest. Physical understanding of these highly nonlinear systems must underlie all applications if we are to get the most out of them. This collection of papers contributes to an understanding of SBS in a variety of important ways.

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