Stimulated Brillouin Scattering Microscopic Imaging

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Two-dimensional stimulated Brillouin scattering microscopy is demonstrated for the first time using low power continuous-wave lasers tunable around 780 nm. Spontaneous Brillouin spectroscopy has much potential for probing viscoelastic properties remotely and non-invasively on a microscopic scale. Nonlinear Brillouin scattering spectroscopy and microscopy may provide a way to tremendously accelerate the data acquisition and improve spatial resolution. This general imaging setup can be easily adapted for specific applications in biology and material science. The low power and optical wavelengths in the water transparency window used in this setup provide a powerful bioimaging technique for probing the mechanical properties of hard and soft tissue.

Brillouin scattering originates from a non-elastic light interaction with acoustic waves in a medium that are generated by thermodynamic fluctuations. The scattered light is shifted in frequency according to the relation

\[ \Omega_B = 2n_0 \frac{\nu}{c} \sin(\theta/2), \]

where \( n_0 \) is the index of refraction, \( \omega \) is the frequency of the incident light, \( \nu \) is the speed of sound in the material, \( c \) is the speed of light in vacuum, and \( \theta \) is the angle between the incoming and backscattered light. The speed of sound for a material depends on properties such as compressibility, shear modulus and density for solids, and pressure, density, temperature, composition and heat capacity for non-ideal gases and liquids. Some of these properties listed above are not easily determined by spectroscopy techniques that interact with atomic or molecular energy levels. Brillouin scattering provides a powerful method to assess these properties. In addition, fluorescent methods often require wavelengths in a specific wavelength range, but Brillouin scattering, similar to Raman scattering spectroscopy, will always give a frequency shift. This allows the option for laser sources that are, for example, cheaper and/or have frequencies that scatter (Rayleigh and Mie) less in the material of interest. Since Brillouin scattering is a label-free, frequency independent method, it opens many new possibilities in biosensing and imaging. Brillouin scattering offers a possible route for deep tissue imaging by selecting a longer wavelength where lossy (Rayleigh and Mie) scattering in tissue is relatively small. Furthermore, the generated signal, being very close in wavelength to the incident light, will also have minimal lossy scattering and transmit out of the sample for detection.

The first published theoretical work predicting the scattering of photons by acoustic phonons was by Brillouin in 1922 and was experimentally verified in crystals and liquids in 1930 by Gross. Over the years, spontaneous Brillouin scattering has been applied to many complex materials such as muscle fibers, bone tissue, eyes, spider silks, thin films and quantized spin waves. A few physical properties of materials that spontaneous Brillouin has been applied to are tensil and compresive strain, temperature, elastic moduli, bulk viscosity, acoustic velocity, refractive index, and phonon lifetime. Brillouin scattering can be performed using surface acoustic waves as well and not just in bulk material. Surface Brillouin scattering has been used to characterize very hard films and thin metal films. Brillouin scattering has also been proposed for remote sensing such as in Brillouin-LIDAR.

Many instrumentation improvements have recently been made for spontaneous Brillouin experiments, particularly for biological applications. Since Brillouin scattering is a non-contact, label free method, it has seen many applications in biology for the measurement of properties that would be difficult to measure with other methods.

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Stimulated Brillouin scattering (SBS) can be treated with a general theoretical model of light scattering from inhomogeneous thermodynamic fluctuations caused primarily by fluctuations in pressure (Brillouin) and temperature (Rayleigh) (see, e.g., Boyd15 Ch. 9). A conceptual picture of stimulated Brillouin for counterpropagating pump and probe beams is shown in Fig. 1. The counterpropagating pump and probes beams with center frequencies at $f_1$ and $f_2$, respectively, beat together in the medium, which will generate and amplify the sound wave in the medium which oscillates at the beat frequency $f_{\text{beat}} = |f_1 - f_2|$. Efficient stimulated Brillouin scattering of the beams will occur only when $f_{\text{beat}} \approx \Omega_B/2\pi$. This nonlinear (stimulated) interaction of light with the medium is due primarily to electrostriction and absorption, however absorption is a small effect for SBS except for lossy optical media16.

In the following derivation and results, we assume that $\omega_1 > \omega_2$, but it is easily applied to the other case. Starting with the equation of motion for a pressure wave1 and using the approximations that phonon propagation distance is small compared to distance that the source term varies dramatically, and assuming steady state conditions, we easily obtain an expression for the acoustic waves. This expression is then used in the wave equation to determine the field propagation. After making the slowly-varying amplitude approximation, using steady state conditions and setting $\omega_1 = \omega_2$ (except for frequency difference terms) since $\omega_1 \approx \omega_2 \approx \omega$, the equations for the spatial rate of change of the intensities of the two fields are

$$\frac{dI_1}{dz} = -g I_1 I_2 - \alpha I_1,$$

(2)
\[ \frac{dI_1}{dz} = -gI_1I_2 + \alpha I_2, \quad (3) \]

where \( \alpha \) is the optical absorption coefficient and \( g \) is the gain factor for SBS. In equation 3, the second term on the RHS has a plus sign since \( I_2 \) is propagating in the negative \( z \) direction (see Fig. 1). The gain factor \( g \) can be broken up into electrostrictive and absorptive factors as

\[ g_B(\Delta) = g_B^e(\Delta) + g_B^a(\Delta), \quad (4) \]

where \( \Delta = \Omega_B - (\omega_1 - \omega_2) \). For optical materials with low absorption \((\alpha \lesssim 10^{-2} \text{ cm}^{-1})\), electrostriction is the dominant effect for SBS generation. For our proof-of-principle experiment, we used water, which has an absorption coefficient of \( \alpha \lesssim 10 \text{ cm}^{-1} \) at \( \lambda = 780 \text{ nm} \). Using equations 2 and 3, we can derive an expression in the very weak probe and undepleted pump limit for the intensity of the probe after the interaction. For a weak probe and for pump intensities sufficiently low such that spontaneous Brillouin from the pump is weaker than the probe, \( dI_1/dz \) is very small. Therefore, in this limit, \( I_1 \) is approximately constant in equation 3. In addition, \( \alpha \) is very small in our case, so the second term on the RHS of equation 3 will be ignored. Solving this equation (integrating from \( L \) to \( z \)) yields

\[ I_1(z) = I_1(L) e^{g_B(L-z)}, \quad (5) \]

where \( g_B = g_B(0) \approx g_B^e(0) + g_B^a(0) \) has been neglected since it is very small for our case). Equation 5 will be used in the results/discussion section to derive the expected order of magnitude for the signal. The exact solutions to equations 2 and 3 (with \( \alpha = 0 \)) leads to a transcendental equation and must be numerically solved. However, looking at equation 3 tells us that increasing the intensity of either or both of the lasers increases the rate of increase of the signal (plotted numerical solutions in15 show this clearly). The expression for the Brillouin shift is given in equation 1, and the Brillouin linewidth (FWHM) can expressed as

\[ \Gamma_B = \frac{(2\eta_s + \eta_d) q^2}{\rho_0}, \quad (6) \]

where \( \eta_s \) is the shear viscosity coefficient, \( \eta_d \) is the dilational viscosity coefficient, \( q = k_1 + k_2 \) is the phonon wavenumber, and \( \rho_0 \) is the average density of the material. The Brillouin gain, \( g_B(0) \) for water is 0.048 m/GW, which is a factor of 3 to 5 less than many alcohols, ketones, or hydrocarbons. Water was chosen for our experiment because the volatility of water is lower than the previous mentioned compounds and was suitable for a long scan with little evaporation.

**Results and Discussion**

A close-up schematic of the imaging setup is shown in Fig. 2. A fixed probe laser and a tunable, counterpropagating pump laser are focused inside a sample to generate the SBS signal. The sample is mounted on a computer controlled xy stage system and scanned across the overlapped focal region of the two counterpropagating beams.

Figure 3 shows a SBS spectrum of H₂O (T = 20.5 °C, reverse osmosis filtered) at one spot on the sample. The scan was performed using a ~26 MHz step size. Using the formulas above, the Brillouin shift and linewidth are calculated to be \( \Omega_B/2\pi \approx 5.06 \text{ GHz} \) and \( \Gamma_B/2\pi \approx 300 \text{ MHz} \) (using viscosity coefficients), and are measured to be \( \Omega_B/2\pi = 5.04 \pm 0.15 \text{ GHz} \) and \( \Gamma_B/2\pi = 245 \pm 30 \text{ MHz} \). This is in agreement with previous experiments15. The dip on the left (at ~5 GHz) and peak on the right for water is 0.048 m/GW, which is a factor of 3 to 5 less than many alcohols, ketones, or hydrocarbons. Water was chosen for our experiment because the volatility of water is lower than the previous mentioned compounds and was suitable for a long scan with little evaporation.
Therefore, will experience $\sim 10^5$ gain with respect to gain of the GW/m$^2$. This yields of water), making detection difficult. By switching to lasers with outputs around several hundred milliwatts, this would drastically increase our SBS signal.

In conclusion, we demonstrated a two dimensional SBS imaging system. As a proof-of-principle, we obtained a two dimensional image using water as the signal medium. Our setup utilized two amplitude modulated CW diode lasers, achieving 25 and 8 mW average power on the sample from the pump and probe, respectively. Comparison

**Conclusion**

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Figure 3. SBS spectrum of water. The loss and gain peaks on the left and right, respectively, are from SBS while the center feature is from absorptive stimulated Rayleigh scattering. The Brillouin frequency shift is measured to be $\Omega_B/2\pi = 5.04 \pm 0.15$ GHz with a Brillouin linewidth of $\Gamma_B/2\pi = 245 \pm 30$ MHz. The grey and magenta bars at the bottom indicate the frequency ranges used for the background (Fig. 4b) and signal (Fig. 4c), respectively, of the image scans.

Gain and L is the total interaction length. For our case, $g_0 = 0.048$ m/GW, $L \approx 2z_\theta \sim 100$ $\mu$m ($z_\theta$ is the Rayleigh length; the signal will come almost entirely where the intensity is the largest), and $I_{pump} \approx 0.6$ GW/m$^2$. This yields $g_0I_{pump} \sim 3 \times 10^{-6}$. Therefore, $I_{s5} \approx I_{probe}(1 + 3 \times 10^{-6}) = I_{probe} + I_{probe} \times (3 \times 10^{-6}) = I_{common\ mode} + I_{signal}$. From this we see that the maximum SBS signal going into the detector is about $10^{-6}$ of the total probe power ($\sim 10^{-4}$ W) going into the detector. Therefore this SBS signal is $\sim 10^{-10}$ W. The shot noise limit of the balanced detector used is $\sim 120$ dB, and the best common mode rejection ratio is close to this ($\sim 118$ dB), therefore the weak signal ($I_{signal}$) will experience $\sim 10^5$ gain with respect of gain of the common mode probe signal ($I_{common\ mode}$). The detector has $\sim 5 \times 10^5$ V/W gain which amplifies the signal to $\sim 10^{-5}$ V. As can be seen in Fig. 3, this is about the expected order of magnitude.

In our experiment, we obtained a 2D image with SBS by scanning a limited region in frequency covering the gain peak for each pixel in the image. For Fig. 4c, each pixel scan took $\sim 1$ min to obtain with the frequency scan range from $\sim 4$–$6.3$ GHz (magenta bar in Fig. 3). The spatial scan step size was $100$ $\mu$m in both dimensions. Figure 4b is a comparison image that was taken with frequency scans from $\sim 3$–$4$ GHz (grey bar in Fig. 3), so the SBS signal is not present. The sample consisted of two glass slides separated by $1$ mm with water sealed between them. On one slide, the logo was etched on the inside of the glass by a CO$_2$ laser cutting machine (Fig. 4a). The lines making up the letters are $\sim 250$ $\mu$m wide. This etch frosts the glass and attenuates the probe beam when scanning over it. Therefore, the signal from water is everywhere except where the logo blocks the probe. By performing a frequency scan (scanning range $\sim 2.3$ GHz with $\sim 50$ MHz steps) for each pixel, a good signal to noise ratio was obtained to discern between signal and backscattered light. In addition, these scans allow for the small drift in the lasers over the duration of the scan without having to lock them.

The present imaging configuration is time consuming and would not be practical for real world applications. Fortunately, this setup can be easily modified to perform similar imaging at much higher acquisition speeds with improved spatial and spectral resolution. For example, a tremendous improvement in frequency stability and low laser power lasers, achieving 25 and 8 mW average power on the sample from the pump and probe, respectively. Comparison
between theory and experiment was made, and improvements in the experiment design for achieving a stronger signal and faster acquisition times was discussed. The methods in this paper are shown to have many benefits for biological applications and provide a unique tool by which samples may be characterized.

Methods
In the experimental setup (Fig. 5), a ~45 mW tunable CW diode laser (Newport, Inc.; Vortex II TLB-6900) is used as the probe beam. The pump laser used is a >100 mW tunable CW diode laser (Sacher Lasertechnik; Lion...
The pump and probe wavelengths were scanned. The probe laser was tuned to the Rb D₂ transition ($\lambda = 780.24\text{ nm}$) and remained untouched for the rest of the experiment. The pump and probe beams were amplitude modulated (Gocho & Housego, 23080-1-LTD AOM) at 102 kHz and 2 kHz respectively. The high modulation frequency substantially reduces the noise in the sample. The difference frequency was output to the lock-in amplifier (Stanford Research Systems; SR830 DSP) for the reference frequency and the time constant was set to 300 ms. A portion of the probe beam (~1 mW) was split off after the electro-optic modulator (AOM) using a CaF₂ window and then attenuated before being used as the reference beam in the balanced detector (New Focus; Nirvana 2007). Both beams were passed through 50 μm pinholes after the AOMs to clean up the spatial beam mode of the diode lasers. The polarization of both beams was filtered by using $\lambda/2$ waveplates and polarizing beam cubes. After the polarizing beam cubes, the two beams were then passed side by side through a $\lambda/4$ waveplate and converted into circularly polarized light in order to easily separate the two beams after the interaction. The counterpropagating pump and probe beams were then focused on the sample using 35 mm and 25.4 mm lenses respectively. The estimated diameters at the focus for the pump and probe beams are ~4 μm and ~7 μm respectively. By the time the pump and probe reach the sample, the average power was 25 mW and 8 mW respectively. The sample was mounted on a xy stage system and was tilted to remove back reflections. After interaction, the beams then travelled back through the $\lambda/4$ waveplate and were now rotated by 90 degrees. In this way, each beam could be removed from the beam paths at the polarization cubes with minimal loss in power. The probe pulse was then attenuated with a neutral density filter (~200 μW) and sent into the balanced detector input. The output signal from the balanced detector is first sent in to a highpass filter to remove the low frequency probe modulation and then sent into the lock-in amplifier. Both lasers, the lock-in amplifier and the xy stage were connected and controlled by a computer using NI LabVIEW. All optics used had an anti-reflective coating for 780 nm.

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Author Contributions
C.W.B., A.J.T., Z.M. and V.V.Y. designed the experiment. C.W.B. built the setup, performed the measurements and analyzed the data. J.V.T and C.W.B. wrote the LabVIEW code to control all the instruments. A.J.T. and Z.M. assisted in the construction of the setup and aquisition of data. C.W.B. wrote the manuscript with M.O.S. and V.V.Y. contributing.

Additional Information
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