Suppression of Stimulated Brillouin Scattering in composite media

M.J.A. Smith, C.M. de Sterke, B.T. Kuhlmey
CUDOS, School of Physics
The University of Sydney
Sydney, NSW 2006, Australia
Email: michael.j.smith@sydney.edu.au

C.G Poulton, M. Lapine, C. Wolff
CUDOS, School of Mathematical and Physical Sciences
University of Technology Sydney
Sydney, NSW 2007, Australia

***Abstract*—Overcoming stimulated Brillouin scattering (SBS) is a major challenge in optical telecommunications networks and in fiber lasers. We evaluate the SBS gain coefficient for an all-dielectric composite material comprising a cubic, subwavelength array of spheres in a uniform background. We demonstrate total SBS suppression in fused silica using GaAs spheres.**

Stimulated Brillouin scattering (SBS) is a prominent effect in nonlinear optics, and describes the process that arises when an incident optical pump excites a coherent acoustic wave in a material [1]. At power levels above the SBS threshold, the induced acoustic wave periodically modulates the dielectric permittivity of the medium, forming a grating which reflects most of the input power. For this reason SBS is widely regarded as a nuisance in both fibre-optic telecommunications [2] and in high power fibre laser design [3], where SBS limits power scaling. To control this effect, researchers have used techniques such as doping [4] and dithering [5]; we outline here an alternative approach involving nanostructuring.

The physical mechanisms behind SBS are photoelasticity and electrostriction, which are expressed as fourth-rank optoacoustic tensors that describe, respectively, the change in the inverse permittivity with a mechanical strain, and the induced stress field from an applied electric field [6]. Here we provide a theoretical framework for numerically evaluating the effective photoelastic and electrostrictive properties of a structured material comprising a cubic array of dielectric spheres in a dielectric background material. We emphasise that there are no known precedents in the literature for evaluating the effective acousto-optic properties of a structured material, despite extensive work on evaluating the effective optical and acoustic parameters of composites [7].

As an example, we evaluate the gain coefficient for a subwavelength composite comprising a cubic array of GaAs spheres in fused silica and show that the gain vanishes when the spheres are close to touching. This example is relevant since silica is the material of choice for optical fibres, possessing low absorption at telecom frequencies and exhibitting strong SBS [8].

Our objective is to minimise the SBS gain coefficient [3]

$$g_{\mathrm{P}} = \frac{4\pi^2\gamma_{\mathrm{xxyy}}^2}{nc\lambda_1^2\rho V_{\mathrm{A}}\Gamma_{\mathrm{B}}}, \tag{1}$$

where $\gamma_{\mathrm{xxyy}} = n^4 p_{\mathrm{xxyy}}$ is an element of the electrostrictive tensor, p_{xxyy} is an element of the photoelastic tensor, Γ_{B} is the Brillouin line width, n is the refractive index, c is the speed of light in vacuum, λ_1 is the incident optical wavelength, ρ is the material density, V_{A} is the long-wavelength longitudinal acoustic phase velocity. The photoelastic tensor p_{ijkl} is defined implicitly via [6]

$$\Delta\left(\varepsilon_{ij}^{-1}\right) = p_{ijkl}s_{kl}, \tag{2}$$

where ε_{ij} denotes the relative permittivity tensor, s_{kl} denotes the strain and summation is implied over repeated indices.

Since the structuring is smaller than both the optical and the acoustic wavelength in the medium, the waves experience an uniform "effective" medium with effective parameters which depend on the properties of the constituent materials as well as on the details of the structuring. The calculation for the effective photoelastic parameter consists of three major parts (see Fig. 1). We (a) determine the effective permittivity of our composite at long optical wavelengths, (b) model the long-wavelength acoustic field by imposing displacements on the boundary of the unit cell and solving the linear equations of elasticity (to obtain a strained cell with an internal strain field). Finally, (c) is similar to (a) but is applied to the strained cell using the strained constituent permittivities.

The effective permittivity is obtained by solving the optical wave equation for a selection of long-wavelength Bloch vectors and equating the volume-averaged energy density to an effective energy density ansatz

$$\mathcal{E}_{\mathrm{avg}} = \frac{1}{2}\varepsilon_0\langle\varepsilon_{ij}E_iE_j^*\rangle = \mathcal{E}_{\mathrm{eff}} = \frac{1}{2}\varepsilon_0\varepsilon_{ij}^{\mathrm{eff}}\langle E_i\rangle\langle E_j\rangle^*. \tag{3}$$

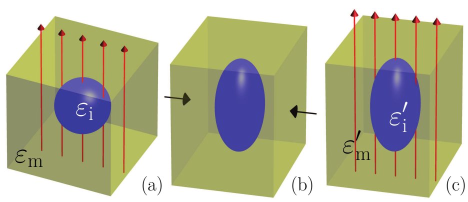

Fig. 1. Outline for calculating $p_{\mathrm{xxyy}}^{\mathrm{eff}}$: (a) compute effective permittivity for unstrained cell, (b) induce s_{xx} strain, (c) compute effective permittivity for compressed cell. Arrows: $\mathbf{E}$ field lines (red), $\mathbf{u}$ (black), $'$: perturbed tensors.

978-1-4673-8603-6/16/$31.00 ©2016 IEEE

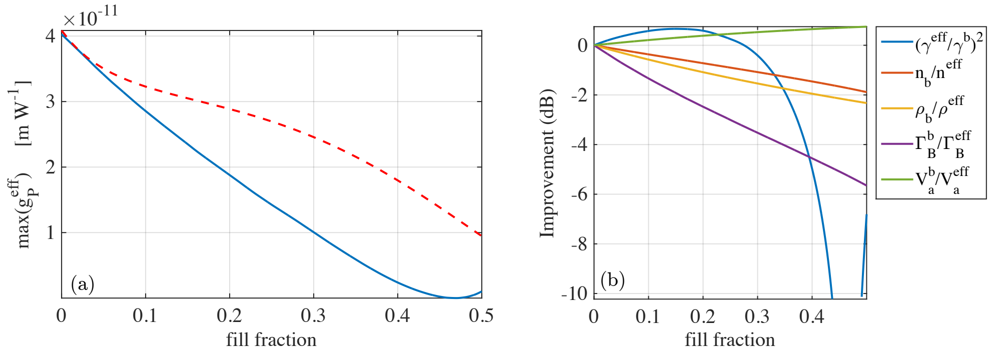

Fig. 2. (a) Effective gain coefficient (blue) and volume average result (dashed), (b) material parameter contributions to the gain, as functions of filling fraction, for cubic lattice of GaAs spheres in SiO_2 (b: background value).

This generates an invertible system of linear equations in $\varepsilon_{ij}^{\text{eff}}$, which is solved straightforwardly. Here $\langle\cdot\rangle$ denotes the cell volume average, ε_0 is the vacuum permittivity and E_j is the electric field distribution of the Bloch mode.

The perturbed geometry and the internal strain field are obtained by solving the equations of linear elasticity [7]

$$\partial_j \sigma_{ij} = \rho \partial_t^2 u_i,\ s_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i), \sigma_{ij} = C_{ijkl} s_{kl}, \quad (4)$$

in the static limit, with the boundary conditions

$$u_j\big|_{\partial W_{\pm \text{x}}} = -D\text{x}\delta_{\text{x}j}\big|_{\partial W_{\pm \text{x}}}, \quad u_j n_j\big|_{\partial W \setminus \{\partial W_{\pm \text{x}}\}} = 0, \quad (5)$$

with C_{ijkl} the stiffness tensor, σ_{ij} the mechanical stress tensor, u_i the displacement, n_j the normal vector at the boundary ∂W of the unit cell (which is symmetric about the origin), δ_{ij} the Kronecker delta, and D a small parameter controlling the magnitude of the compression. The boundary conditions (5) correspond to a $s_{\text{xx}}^{\text{eff}} = -D$ strain for the composite material. Using this strained configuration, we repeat the first step and compute the permittivity of the strained geometry. Comparing the unstrained and strained inverse permittivity tensors, in addition to using the symmetry properties of cubic materials, $p_{\text{xxyy}}^{\text{eff}}$ is then recovered. Having determined the effective photoelastic parameter for a bulk composite material, evaluation of the remaining effective parameters in the SBS gain coefficient (1) is relatively straightforward [9].

For our chosen example of GaAs spheres in a silica background, the SBS gain coefficient versus filling fraction f is given in Figure 1a (blue), for an incident pump wavelength $\lambda_1 = 1.55\,\mu\text{m}$ and lattice period of $50\,\text{nm}$. The choice of period ensures the subwavelength assumption is satisfied and that there are approximately 10 cells per optical wavelength in the material. The effective gain coefficient for our composite monotonically decreases with filling fraction for $0\% < f < 47\%$ and vanishes at $f = 47\%$ due to a sign change in the effective photoelastic parameter. For comparison we include an effective gain coefficient calculated using simple volume averaging of all parameters in (1) (dashed red). This approach is only approximately similar for very dilute filling fractions ($f \lesssim 5\%$), despite the structuring being subwavelength. This emphasises the importance of the full numerical treatment used here to determine the gain. In Figure 1b, we show all effective material parameters for our composite and consider their individual effects on the SBS gain coefficient via

$$10\log_{10}\left(\frac{\max(g_{\text{P}}^{\text{eff}})}{\max(g_{\text{P}}^{\text{b}})}\right) = 10\log_{10}\left(\left(\frac{\gamma}{\gamma^{\text{b}}}\right)^2\right) + \ldots \quad (6)$$

Fig 1b shows that the electrostriction reaches a maximum at $f = 15\%$, an 8% enhancement compared to pure silica, and that all materials contribute to the reduction of the gain above $f \approx 27\%$ with the exception of the acoustic velocity.

In conclusion, we show that the effective SBS coefficient can be controlled by subwavelength structuring of a material. Although we have shown the ability to suppress SBS, it can be enhanced in this way as well.

References

[1] G. P. Agrawal, *Nonlinear fiber optics*, 2nd ed. San Diego: Academic press, 1995.

[2] E. Peral and A. Yariv, "Degradation of modulation and noise characteristics of semiconductor lasers after propagation in optical fiber due to a phase shift induced by stimulated Brillouin scattering," *IEEE J. Quantum Elect.*, vol. 35, no. 8, pp. 1185–1195, 1999.

[3] A. Kobyakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin scattering in optical fibers," *Adv. Opt. Photonics*, vol. 2, no. 1, pp. 1–59, 2010.

[4] P. Dragic, T. Hawkins, P. Foy, S. Morris, and J. Ballato, "Sapphire-derived all-glass optical fibres," *Nat. Photonics*, vol. 6, no. 9, pp. 627–633, 2012.

[5] M.-C. Ho, M. E. Marhic, K. K. Wong, and L. G. Kazovsky, "Narrow-linewidth idler generation in fiber four-wave mixing and parametric amplification by dithering two pumps in opposition of phase," *J. Lightwave Technol.*, vol. 20, no. 3, p. 469, 2002.

[6] R. E. Newnham, *Properties of Materials: Anisotropy, Symmetry, Structure: Anisotropy, Symmetry, Structure*. New York: Oxford University Press, 2004.

[7] G. W. Milton, *The theory of composites*. New York: Cambridge University Press, 2002.

[8] W. Gambling, "The rise and rise of optical fibers," *IEEE J. Sel. Top. Quant.*, vol. 6, no. 6, pp. 1084–1093, 2000.

[9] M. Smith, B. Kuhlmey, C. M. de Sterke, C. Wolff, M. Lapine, and C. Poulton, "Metamaterial control of stimulated Brillouin scattering," *arXiv preprint arXiv:1602.03222*, 2016.