Stimulated Brillouin Scattering in Silicon Waveguides

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INTRODUCTION

1. Stimulated Brillouin Scattering

The stimulated Brillouin scattering originated from constructive reinforcement of the acoustic and Stokes waves in the spontaneous Brillouin scattering [1]. As the incident and scattered light fields beat together, the density and pressure in the media vary as a result of electrostriction. Such density variations give rise of refractive index variation, which will further be scattered off by the incident laser field. The scattered light, at the Stokes frequency, will add constructively with the Stokes radiation that produced the acoustic disturbance. The two waves grow to larger amplitudes in this way, seen as the stimulated Brillouin scattering.

Tailorable stimulated Brillouin scattering (SBS) gives the chance to modulate signal frequency, thus can be utilized in Silicon photonics, microelectromechanical systems and signal-processing technologies [2][3].

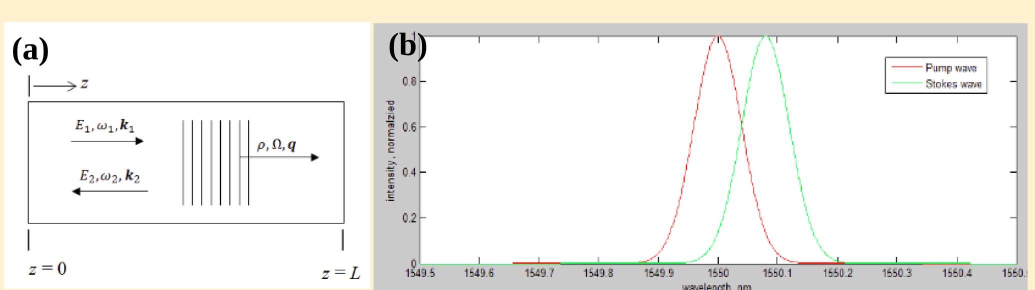


Figure 1. Stimulated Brillouin scattering (a) Incident wave (pump wave) E1 and Stokes wave E2 [1]. (b) total wave profile at SBS threshold

2. Silicon Wire Waveguides, Photonic Crystal Waveguides and Nanocavities

Recently it has been theoretically found that giant enhancement of SBS exists in silicon waveguides [4]. The contrast in propagation of both optical waves and acoustic phonons between air and silicon contributes to both the electrostriction and radiation pressure, giving an SBS-gain of possibly times greater in silicon wire waveguides than in conventional silica fibers.

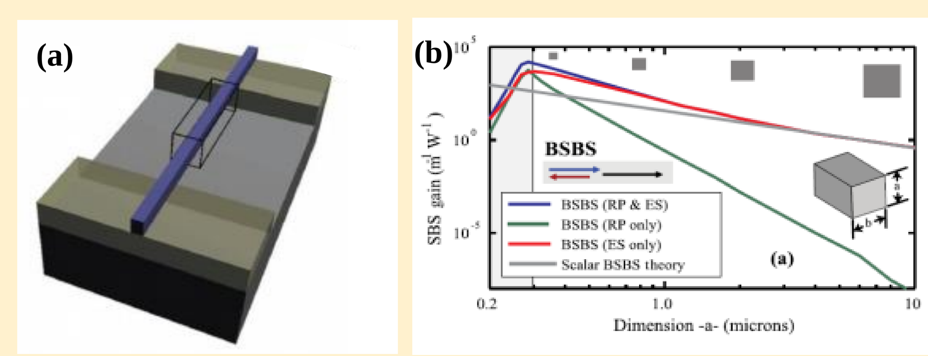


Figure 2. (a) Silicon suspended membrane waveguide (b) Computed SBS contributions from electrostriction (ES) and radiation pressure (RP) with relation to the silicon suspended membrane waveguide dimension a and b (for b=0.93a) [4].

Here we presented an attempt to calculate, measure and compare the SBS gains in different optical waveguides, including the highly nonlinear fiber and silicon waveguides.

We proposed to design long silicon suspended membrane waveguides [5] for enhancing on-chip stimulated Brillouin scattering and verify the designs by FDTD simulation tools.

Since that slow light in photonic crystal waveguides show possibility on enhanced nonlinear effects [6][7], we also proposed to use photonic crystal structure to enhance on-chip SBS.

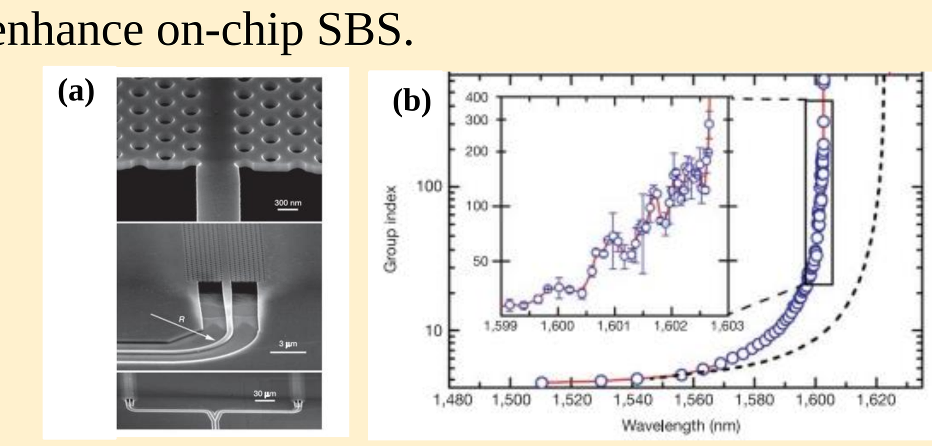


Figure 3. (a) SEM images of a Mach-Zehnder Interferometer (MZI) using photonic crystal waveguides. (b) Plot of group index in the signal arm and the reference arm from the MZI. [8]

The current goal is narrowed down to design and fabricate a proper photonic crystal (PhC) nano-cavity with acceptable Q-factor and strong resonance in SBS peaks at telecommunication frequency.

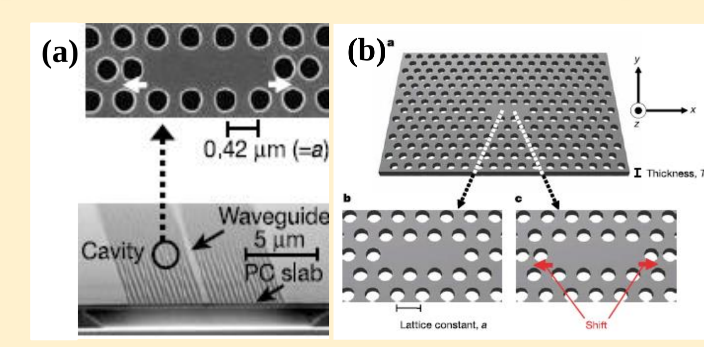
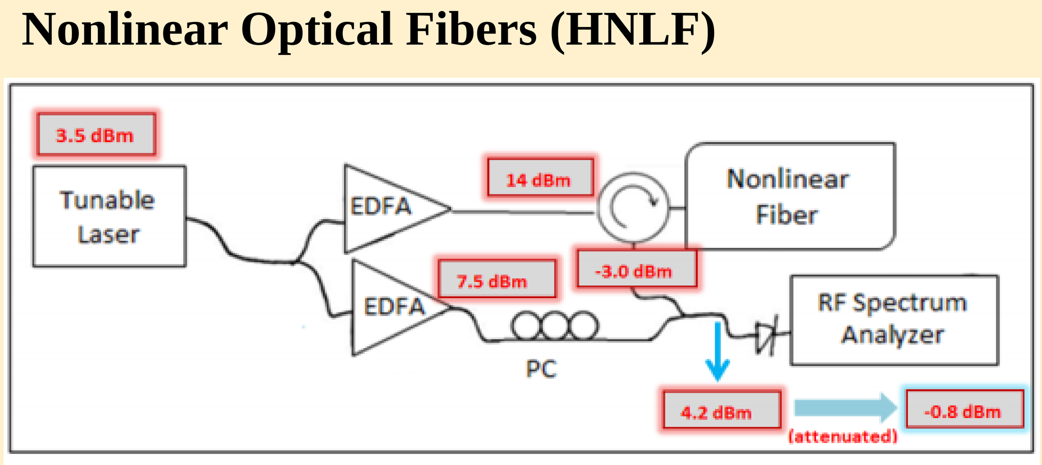


Figure 4. PhC nanocavity with extremely high Q-factor achieved by position shifting of the holes nearby cavity. (a) SEM images (b) schematic graph of the designs [9]

EXPERIMENTS AND SIMULATIONS

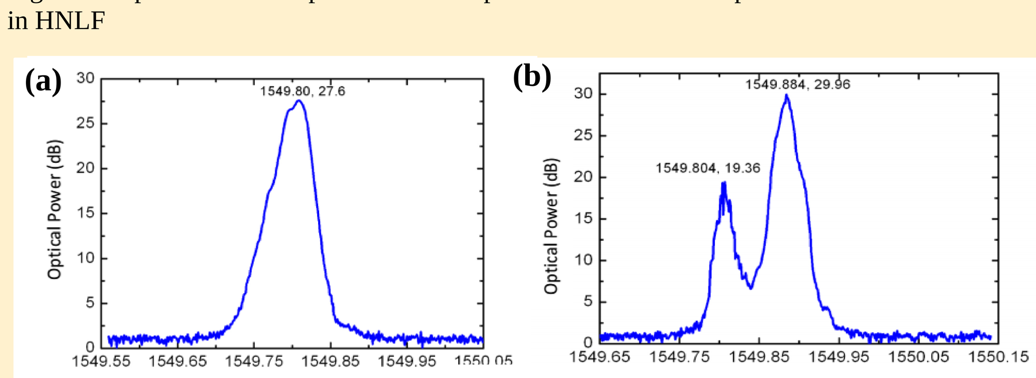
1. Stimulated Brillouin Scattering in Highly Nonlinear Optical Fibers (HNLF)



$$\tilde{E}_{mix}(z,t) = \tilde{E_1}(z,t) + \tilde{E_2}(z,t) = A_1(z,t)e^{i(k_1 z-\omega_1 t)} + A_2(z,t)e^{i(k_2 z-\omega_2 t)} + c.c.$$

$$I = |\tilde{E}_{total}|^2 = I_0 + I_2 + 2\sqrt{I_0 I_2}\cos[(\omega_2-\omega_1)t].$$ [10][11]

Figure 5 Experimental set-up and measured power levels at critical points for SBS measurement in HNLF



$$\omega_2 - \omega_1 = \frac{c}{\lambda_2} - \frac{c}{\lambda_1} = \frac{c(\lambda_1-\lambda_2)}{\lambda_1\lambda_2} \approx \frac{3\times10^8\,\text{m/s}\times(0.08\,\text{nm})}{(1550\text{nm})^2} \approx 9.990\ \text{GHz}$$

Figure 6 (above) Analyzing the Brillouin frequency (a) the input optical spectrum (b) the output optical spectrum

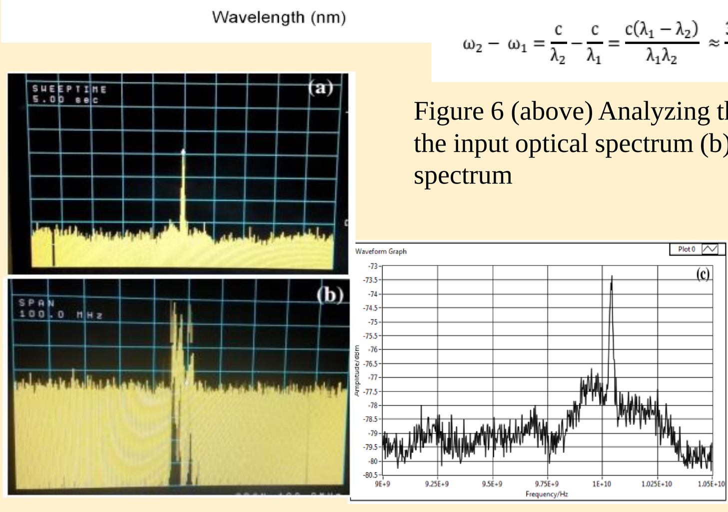


Figure 7 Analyzing the Brillouin frequency using radio-frequency spectrum analyzer (a) with span of 2GHz (b) with span of 100MHz (c) with time-average over 100 values, extracted using LabVIEW.

2. Design of Photonic Crystal Waveguide with Appropriate Bandgap

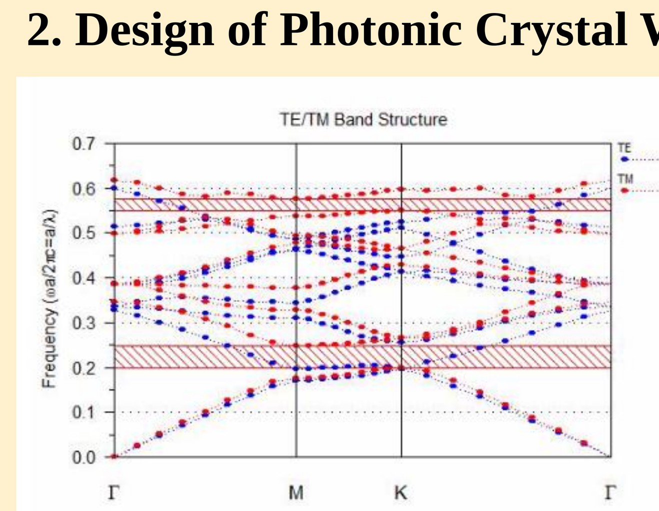


Figure 8 Band diagram of a hexagonal photonic crystal lattice produced using *Rsoft Bandsolve*

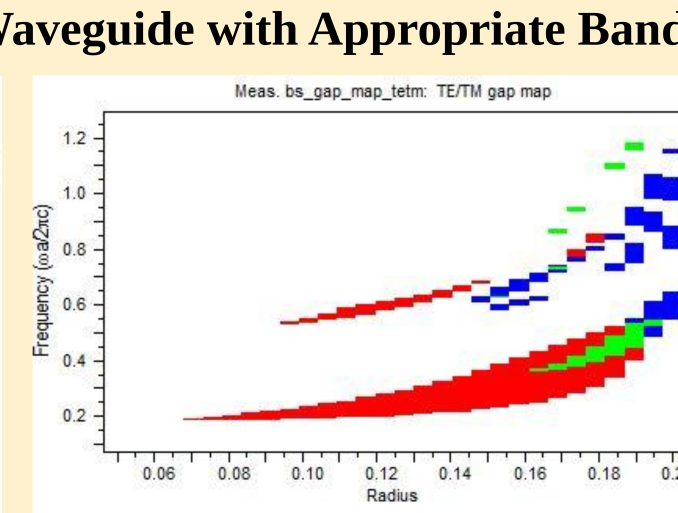


Figure 9 Bandgap (in frequency) of photonic crystal lattice with relation to hole radius (in micron)

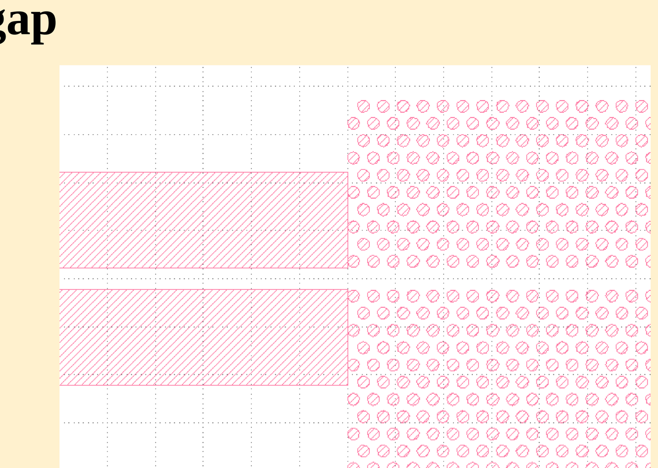


Figure 10 Detailed look of a photonic crystal waveguide, produced using *OptoDesigner* by *PhoeniX*

3. Design and Simulation Results of Photonic Crystal Cavities

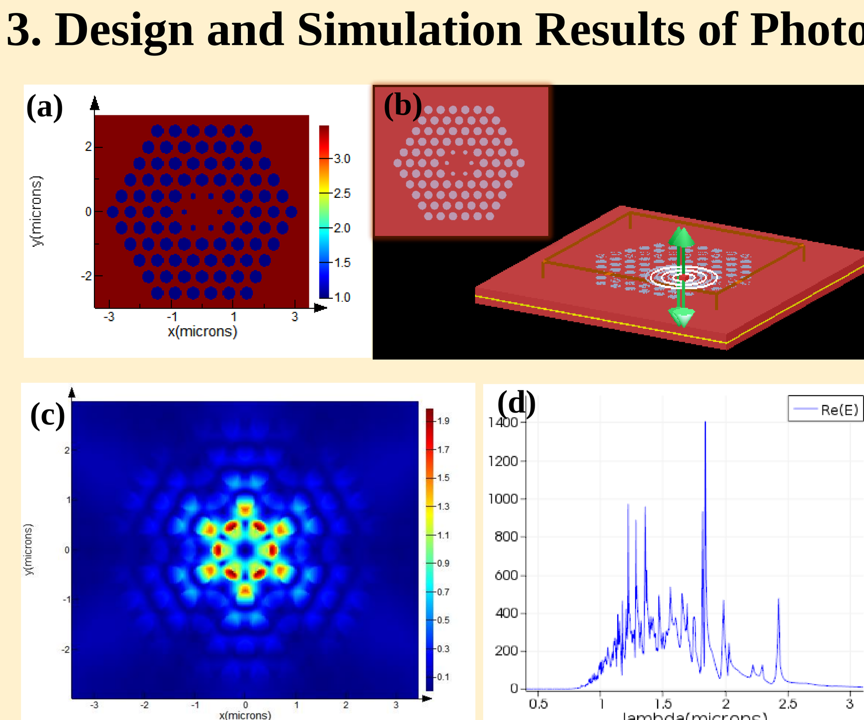


Figure 11 (a) Reflective index map of the structure from top view (b) simulation set-up of silicon hexagonal photonic crystal cavity with two dipole sources (c) E-field showing confinement inside the cavity (d) spectrum showing resonance peaks at about 1215 nm and1834 nm. The graphs are produced using *Lumerical FDTD Solutions.*

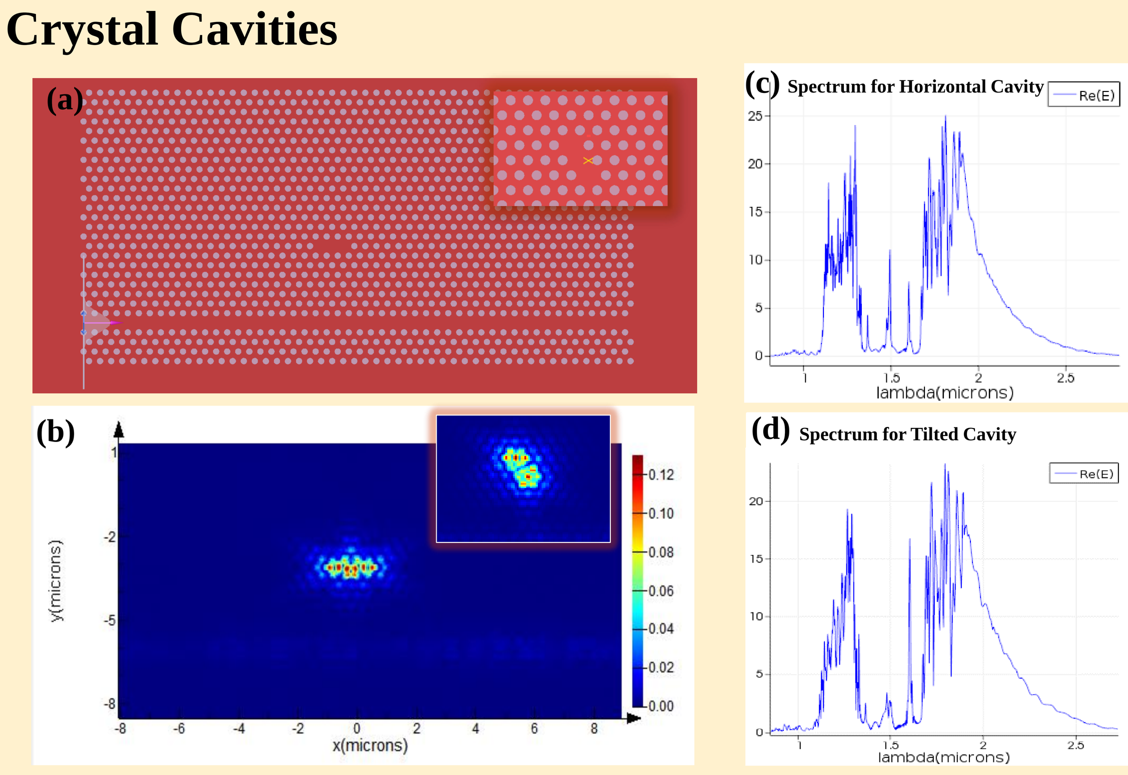


Figure 12 (a) Horizontal silicon photonic crystal cavity with Gaussian wave source coupled from a straight waveguide, corner view showing a tilted cavity instead (b) E-field showing light confinement inside the horizontal cavity, corner view showing E-field confinement in a tilted cavity (c) E-field spectrum in horizontal cavity (d) E-field spectrum in tilted cavity. The graphs are produced using *Lumerical FDTD Solutions.*

DISCUSSIONS

1. Limitations for the SBS Measurement Set-up

We examined the SBS in HNLF with the lowest input power of about 25~37 mW, which is comparable to the theoretical calculation of 24mW for such optical fiber. Direct dependency of the SBS beating signal intensity on input pump power was shown by experiments of SBS in HNLF. However, the power level of the beating signal is much lower than expected, resulting from the instability of the system and noise flow. Reduction of reflections and other methods were used to minimize the noise. To further improve the results, we suggested adding optical isolators, filters or feedback stabilization systems.

2. Design of Silicon Photonic Crystal Lattice

We optimized the design of Silicon PhC lattice with lattice constant a = 0.42 um, radius r = 0.12 um. The thickness of the slab was 0.25um.

2. Design and Simulation of PhC Nanocavities

The horizontal PhC nanocavity has a Q-factor of about 2020, two peaks at 1294 nm and 1809 nm. The tilted one with Q-factor of about 1340, two peaks at 1263 nm and 1791 nm. The separation of the resonance wavelengths may not be small enough for enhancing SBS frequencies inside the cavity.

CONCLUSION

Despite the promising applications with enhanced on-chip SBS in nanoscale silicon devices, it remains hard to design and fabricate such devices. The device typically has to be long while maintaining ultra-low loss, which is hard to fabricate. We would continue to explore possibilities with silicon suspended membrane waveguides and PhC nanocavities.

REFERENCES

[1] G.P. Agrawal, Nonlinear Fiber Optics, 5th ed., Elsevier Inc., (2013).

[2] Z. Zhu, D. J. Gauthier, and R. W. Boyd, "Stored light in an optical fiber via stimulated Brillouin scattering,". Science 318(5857).

[3] M. J. Damzen, R. A. Lamb, and G. K. N. Wong, "Ultrashort pulse generation by phase locking of multiple stimulated Brillouin scattering," Opt. Commun.82(3-4), 337–341 (1991).

[4] P. Rakich, C. Reinke, R. Camacho, P. Davids, and Z. Wang, "Giant enhancement of stimulated Brillouin scattering in the subwavelength Limit," Phys. Rev. X 2, 1–15 (2012).

[5] Z. Cheng, X. Chen, C. Y. Wong, K. Xu, and H. K. Tsang, "Mid-infrared Suspended Membrane Waveguide and Ring Resonator on Silicon-on-Insulator," Photonics Journal, IEEE 4, 1510-1519 (2012).

[6] A. Hosseini, X. Xu, D. N. Kwong, H. Subbaraman, W. Jiang, and R. T. Chen, "On the role of evanescent modes and group index tapering in slow light photonic crystal waveguide coupling efficiency," Appl. Phys. Lett.98, 031107 (2011).

[7] Y. A. Vlasov and S. J. McNab, "Coupling into the slow light mode in slab-type photonic crystal waveguides," Opt. Lett. 31, 50–52 (2006).

[8] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, "Active control of slow light on a chip with photonic crystal waveguides," Nature 438, 65-69 (2005).

[9] Y. Akahane, T. Asano, B. S. Song, and S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," Nature 425, 944-947 (2003).

[10] R. W. Boyd, Nonlinear Optics, 3rd. Ed, Academic Press (2008)

[11] B. E. A Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, Inc.,(1991).