10-2012

Surface Optomechanics: Analytic Solution of Detection Limits of Surface Acoustic Waves in Various Fluids

John Zehnpfennig II

David D. Covell

Matthew R. Letarte

Kraig E. Sheetz

James J. Raftery Jr.
United States Military Academy

Surface Optomechanics: Analytic Solution of Detection Limits of Surface Acoustic Waves in Various Fluids

Conference Paper · October 2012

DOI: 10.1364/FIO.2012.FW4B.3

John Zehnpfennig
United States Military Academy West Point

Matthew Letarte
United States Military Academy West Point

Kraig E Sheetz
Mount Saint Mary's University, Emmitsburg

James J. Raftery, Jr.
United States Military Academy West Point

Surface Optomechanics: Analytic Solution of Detection Limits of Surface Acoustic Waves in Various Fluids

John Zehnpfennig, David Covell, Matthew Letarte, Kraig E. Sheetz, James J. Raftery, Jr.,
Photonics Research Center, United States Military Academy, West Point, NY 10996
john.zehnpfennig@usma.edu

Abstract: Here we derive the absolute detection limits of various families of surface acoustic waves (SAW) resulting from Brillouin scattering in a whispering gallery resonator (WGR). Given this limit, we calculate the absolute concentration limits for detection of pollutant chemicals in air, water, or other fluids surrounding the WGR. General equations for SAW velocity, linewidth, and detectability are given.
OCIS codes:

1. Introduction

Surface optomechanics on WGR is currently an area of intense fundamental study [1-3]. Several years have passed since the ideal Brillouin scattering-induced acoustic equations [4] were derived to prove conservation of momentum, energy, and frequency. Fig. 1 illustrates a SAW and its deformation profile.

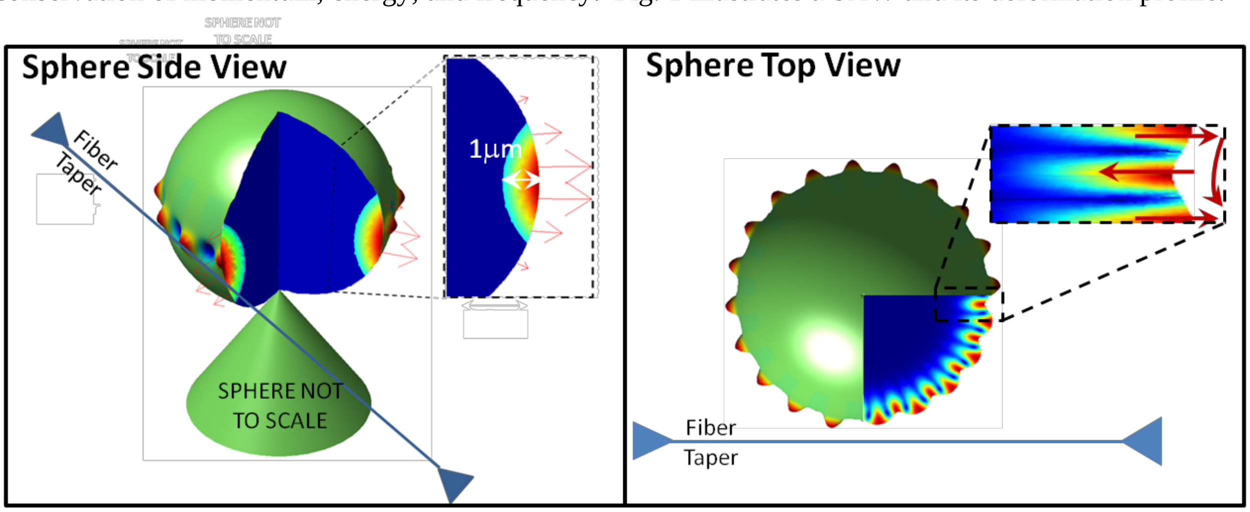

Fig. 1. Graphic of FEM-calculated SAW [5].

2. Calculating Effective Limits of SAW Sensing

We have recently calculated [6] frequency shift of a Love-type SAW on an opto-mechanical WGR in air as the concentration of gaseous CO_2 within the air varies. Here we report an analytic method of predicting frequency shifts due to changing concentrations of a pollutant in a fluid – liquid or gas – surrounding a WGR. It is to be noted that this is an open-cavity system, wherein the resonator must only be present in the environment, and need not be enclosed.

The SAW is a hyper-acoustic wave oscillating at frequencies between 50MHz and 12GHz [2, 7], dependent upon the resonator medium and SAW family. The velocity of the surface acoustic wave, v_{SAW} is related to the speed of sound in the resonator material, v_{bulk}, and the speed of sound in the fluid surrounding the WGR, v_{fluid}, in the following manner:

$$v_{SAW} = \alpha v_{bulk} + \beta v_{fluid} \tag{1}$$

where α is related to the portion of the wave contained in the bulk medium and β is related to the portion of the wave propagating in the fluid surrounding the resonator. α and β are determined by cross-sectional area, deformation intensity, and linewidth. These qualities are directly related to the family of SAW waveform, such as longitudinal, transverse, Rayleigh, Lamb, Love, and so on. Available SAW waveform families on a WGR are the same as those known in geophysics.

A novel application of such SAW is the detection of ambient chemical concentrations in the environment surrounding the resonator. Detection of chemical concentration relies upon two factors: the frequency shift of resonant SAW mode due to increased concentration, and linewidth of the SAW.

Using analytical and FEM calculations and empirical results, we determine the frequency shift of various pollutant fluids in air, and increased the concentration of the pollutant. We found that as a more dense pollutant material entered the environment, the higher the frequency shift. The greater the molecular density of the pollutant, the steeper was the slope of frequency increase. This implies that the density of the pollutant material directly affects the speed of sound on the resonator.

Likewise, the limits of detection are directly tied to frequency shift and SAW linewidth. Both of these factors are related to the direction of SAW-mode propagation and azimuthal mode number. As mode number increases, the sensitivity of the SAW to the environment will decrease as the β factor decreases, however the linewidth of the SAW will narrow relative to lower azimuthal-mode SAWs of the same family due to conservation of energy[8]. At some point, there exists an optimal balance between frequency shift and azimuthal mode; this is the optimal SAW azimuthal mode number. We calculate these for several families of SAW deformation and demonstrate the results.

3. Conclusions

Here we provide analytic solutions to SAW velocity, the related frequency shift based upon pollutant concentration change, and finally the limits of detection. This work may lead to ultra-sensitive pan-species chemical agent detectors. Using non-sensitized WGR materials to observe frequency shift and slope of shift, it is likely possible to use the same device to detect many or all pollutants in a fluid environment. Because this system is pumped and interrogated via fiber optic, pan-species remote sensing over large areas or volumes may soon be realized.

4. References

[1] G. Bahl, J. Zehnpfennig, M. Tomes, and T. Carmon, "Stimulated optomechanical excitation of surface acoustic waves in a microdevice," *Nature Communications,* vol. 2, p. 6, 26 July 2011 2011.

[2] J. Zehnpfennig, G. Bahl, M. Tomes, and T. Carmon, "Surface optomechanics: calculating optically excited acoustical whispering gallery modes in microspheres," *Optics Express,* vol. 19, p. 9, 2011.

[3] A. Cho, "Putting Light's Light Touch to Work As Optics Meets Mechanics," *Science,* vol. 328, p. 2, 2010.

[4] R. W. Boyd, *Nonlinear optics*. San Diego, CA: Academic Press, 2003.

[5] J. Zehnpfennig, "Surface Optomechanics: Forward and Backward Scattered Surface Acoustic Waves in Silica Microsphere," Masters Thesis,University of Michigan, ProQUEST, 2011.

[6] J. Zehnpfennig, M. Letarte, R. W. Sadowski, and J. J. Raftery Jr., "Surface Optomechanics: Calculation of Love Surface Acoustic Waves on Microresonators," presented at the Conference on Lasers and Electro Optics 2012, San Jose, CA, 2012.

[7] M. Tomes and T. Carmon, "Photonic micro-electromechanical systems vibrating at X-band (11-GHz) rates," *Physical Review Letters,* vol. 102, p. 113601, 2009.

[8] T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer, and K. J. Vahala, "Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity," *Physical Review Letters,* vol. 95, p. 033901, 8 2005.