**Near-field analysis of high-frequency vibrations of nanoscale structures**

(Alternative title: Mechanical nanoindentation by optical near-field spectroscopy)

**Scientific Abstract**

The use of light as a measurement tool dates back centuries if not millennia. While being flexible and robust, optical characterization techniques are limited to the analysis of electromagnetic properties and do not provide all the necessary physical information about the inspected sample.

The acoustic spectrum carries information about the elastic and structural properties of devices. However, since features are becoming increasingly small, the far-field signal is composed of tens or even hundreds of inelastic scatterers, making it hard to distinguish the structural deviations of interest from normal variations.

doesn't provide (spatial) specificity

time scales - their natural vibration frequency scales accordingly

* BMS/BLS
* Picosecond ultrasonics, as its name implies, – mechanical characterization at extremely short time scales (with metal line-space transducers or contactless). Relies on some sort of excitation mechanism. Low lateral resolution.
* AFM-based methods allow very fine lateral resolution but are quasi-static.
* s-SNOM enables FTIR and pump-probe spectroscopy at nanoscale. Tip-enhanced Raman spectroscopy has also been demonstrated.

Near-field microscopy offers the unique advantage here of allowing access to localized and confined fields through evanescent coupling.

couple to far-field radiation

Novelty: This proposal aims to combine the advantages of BLS to analyze extremely fast acoustic excitations with the spatial resolution provided by the AFM, to allow the measurement of mechanical response in the GHz range at nanoscale.

Laser Doppler vibrometer for nanostructures.

1. **Scientific background**

*What is the current situation/state-of-the-art in the field? Identify the gap in knowledge or issue not being addressed by existing studies that creates a need for this line of inquiry.*

Brillouin-Mandelstam light scattering (BMS/BLS) spectroscopy is an important technique for nondestructive and contactless mechanical characterization of microstructures.

Successful applications include studies of biological systems, polymers, …

Can also photo-excite excitons (bound electron-hole pairs), plasmons (quanta of plasma oscillations), magnons (quanta of spin waves) and more.

1. Hybrid technology of III-V on top of SOI is extremely successful and extremely important. It brings about a broad portfolio of active devices… It is now even possible to use direct growth instead of bonding, in certain cases
2. Still, the platform is being used and studied strictly from an electro-optic standpoint
3. There are still things we cannot do, such as narrowband filtering, long delays, isolators, analog processing at broad bandwidth…
4. Opto-mechanics promises to bridge this gap… interactions between guided light and sound…
5. Many demos in silica, silicon-nitride, chalco, even silicon!
6. Also many demos in piezo-electric materials such as GaAs and AlN. Inspiration from the SAW devices of the analog electronics era.
7. Demonstrations of applications in microwave photonics
8. Still, no considerations of the opto-mechanics in the hybrid platform of III-V on SOI…

Depth info (same elastic properties)

- BLS / BLS for bio studies – resolution + a Brillouin spectrometer

Elastic properties are modified at nanoscale

- Transient Gratings – nano-resolution but in 1D. We want to measure structures and not only layered media.

- Nanolayers, Membranes (the Greek guy)

However,

Current gaps of the far-field BLS spectroscopy: spatial resolution and measurement precision of the structural parameters of interest (especially when it comes to 10’s or even 100’s GHz frequencies). Also, the overall throughput of such systems is poor (minutes or even hours). Also cross-sensitivity

Besides, BLS assumes periodic patterns, but in practical electronic devices (logic) not all structures within the illuminated spot are the same.

Optical Critical Dimension (OCD) spectroscopy - Optical Scatterometry

Alternatives to optical metrology:

* Backside US excitation
* XRD – expensive (also can’t use the flexibility of squeezed light)
* 2020; AFM for nanoscale mechanical property characterization; 2021; Acoustic subsurface-AFM - 3D imaging at the nanoscale;

SNOM has gained large interest in the community. Study of wave phenomena, particle and quasi-particle phenomena. Common to all is the need for high spatial resolution.

1. **Research objective and expected significance (**and implications**)**

*Objectives: Describe the main aims of your research. Please write from the perspective of, “in this study I intend to…”*

*Significance & implications: What are the immediate and more secondary implications of the results attained/knowledge gained? What fields are likely to benefit? What further research might it enable, etc.? End with a “selling point” to inspire the reviewer regarding the importance of your proposed research.*

In this study I intend to realize the first near-field BLS system that will measure acoustic excitations.

Use light!

Carry over the far-field BLS analysis methods to a near-field system.

Significance and potential implications:

* The hybrid platforms are actually very important, for introducing active functions to silicon photonics such as laser diodes, semiconductor optical amplifiers, photo-detectors for telecom wavelengths, and high-rate modulators. Therefore the program relies on platform that is growing very fast. Nowadays it is also possible to grow III-V layers directly on top of silicon instead of bonding.
* The introduction of opto-mechanics will make this critical electro-optic platform even richer, with potential for piezo-electric transduction and detection, surface-acoustic wave devices, long delay lines, narrowband filtering and correlation-domain processing of high-frequency waveforms without sampling and digitization, opto-mechanical sensing, and narrowband laser diode sources.
* The hybrid platform provide large flexibility in confinement of optical and acoustic modes to either layers
* It possible to confine carriers, photons and phonons all in small and controllable volumes
* Devices may benefit from electro-optic as well as opto-mechanical gain together. Both may be controlled.

Spatial resolution / Sensitivity / Access to vibrational modes that do not scatter to far field (near-field has a “cone” of k vectors)

Additional benefits of the developed methods:

10 GHz - photonic structures (meta optics) for short wavelengths

100 GHz - relevant for semiconductors (integrated electronics)

<https://www.kmlabs.com/nanoscale-acoustic-metrologies>; <https://www.kmlabs.com/nanoscale-energy-transport>;

Fundamental studies: - Study of thermal transport at nanoscale; - Study of charge transport at nanoscale;

Recombination time can be measured with THz.

Can we measure the deformation potential (carrier excitation and relaxation dynamics) from near-field scattering?

Measure SPP - Yura

1. **Detailed description of the proposed research**

*Provide a brief overview of a methodology that clearly relates to the stated objectives.*

**3.1 Working hypothesis**

Tip-sample distance dependence - Displacement

Sample EM properties dependence - Elasto-optic effect - a change in the refractive index of the sample can be induced by the acoustic wave through the photo elastic effect

RI perturbations associated with acoustic waves are extremely weak.

In-plane k component; Chris Körner - spatially-resolved detection of magnetic excitations

Q: How is the phase-matching issue resolved in EO modulators?

Demodulation of the inelastic component was shown possible in other physical platforms or at low frequencies:

1) They measure spin-wave excitations by near-field Brillouin light scattering (by demodulating the inelastically scattered component using an optical filter).

We will need to measure the acoustic (not spin-wave) excitations at the surface of the sample using similar principles.

2) Raman (TERS)

3) They electrically demodulate the inelastically scattered component. (low frequencies?)

**3.2 Research design and methods**

Modeling (Analysis and simulations of…)

The incident light is scattered off the coupled tip-sample system.

* Estimate the strength of the scattered optical field Es as a function of RI perturbations associated with acoustic waves at the sample surface.
* It may prove useful to adapt the “coupling weight function” formalism (in the attached example) to our case of acoustic phonons.

The tip-sample interaction is expressed through the effective polarizability which also depends on the sample permittivity.

Model the tip-sample interaction when the tip is placed above a vibrating structure

In our case, a change in the refractive index of the sample can be induced by the acoustic wave through the photo-elastic effect.

(In the work I attached, we estimated the photo-elastic RI perturbations to be roughly 10^-6, but it can be many orders of magnitude smaller depending on the acoustic excitation strength and elasto-optic tensor of the material.)

Pls try to estimate how small are the changes in refractive index that a stated-of-the-art s-SNOM system can resolve?

Main methodologies:

* Numerical analysis of optical modes
* Numerical analysis of acoustic modes (Applied results?)
* Optimization of tip materials and dimensions.
* Calculations of opto-mechanical interactions
* Calculations of competing nonlinear effects such as two-photon absorption and free-carrier-induced absorption
* Fabrication of SOI waveguides with varying depth and width
* Wafer bonding
* Subsequent processing of III-V layers
* Deposition of metals
* Test-and-measurement station
* Extension from InP to GaAs: the introduction of piezo-electricity

Experimental system roadmap (project steps):

* Spont - optically measure spontaneous acoustic excitations which already exist in the sample
* Electrically stimulated
* Optically stimulated (spont. has low SNR -> minutes or even hours)
* Squeezed (2021; Quantum-enhanced nonlinear microscopy; 2020; Photonic quantum metrology;) – copy&paste from the proposal with Eliran
* Pulsed (optically stimulated)
* Pulsed (ultrafast)

Samples:

- Fabricate samples with polymer nanolines of varying width and height (continuous and stepwise) and measure with SNOM.

- Obtain piezoelectric devices with IDTs and generate intense SAWs of different frequencies and measure the surface displacement.

**3.3 Preliminary results**

*Adequacy of PI (example: Omri Eran, Nimrod)*

* Optical, acoustic, and opto-mechanical mode-solving (also based on Eric). Note on two-photon absorption
* SOI fabrication in Bar-Ilan and Tower, ARMA as example of capabilities
* SBS on chip: Shahar
* SAW in SOI
* Bonding of InP to SOI at Bar-Ilan, PETA-CLOUD
* Some stuff from fiber opto-mechanics (Got to mention the Nature-Comm).
* My personal extensive experience in engineering optical inspection and metrology tools (elastic domain).
* Wavefront correction of an acousto-optic scanner
* My personal extensive experience in high-precision optical measurements of weak acoustic signals (inelastic domain).
* Q: Do I need letters of support from colleagues? Letter of intent for research collaboration?

**Available resources and infrastructure/facilities**

*Adequacy of infrastructure*

Added value of group for the particular project:

* We do SOI, bonding, and opto-mechanics in SOI and fiber. Now we can combine all these together.

**Expected results, possible pitfalls, fallbacks and risk mitigation strategies**

Far field BLS

TERS

Test the hypothesis on SAW devices

(\* purchase "surface acoustic wave" "50 GHZ" device  commercially available \* https://swegan.se/stg\_5ab50/?page\_id=1358 \* saw device  "wires soldered to the electrodes" "sma connector" \* Gan-on-sic surface acoustic wave devices up to 14.3 Ghz)