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Direct RF to Optical Link Based on Film Bulk Acoustic Wave Resonators (FBAR)

Aleem M. Siddiqui, Jeremy Moore, Matthew Tomes, Paul Stanfield, Ryan Camacho, and Matt Eichenfield

Sandia National Laboratories, Albuquerque, NM 87185, USA

E-mail: meichen@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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FBAR based Optical Modulator

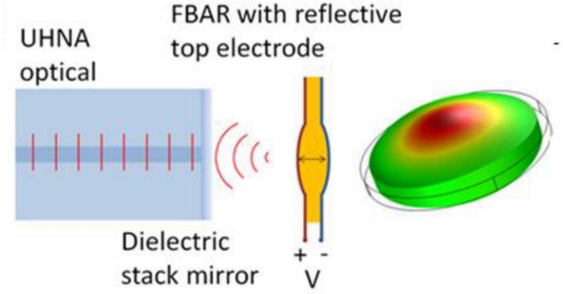
- Introduction
- Overview of FBAR concept
- Theoretical Analysis of System Performance
  - Optical Characteristics
  - RF/mechanical Characteristics
- Experimental Demonstration
  - Electrical Characterization
  - Optic Characterization
  - System Performance
- Conclude

Introduction

- Variety of approaches to phase modulation
  - Silicon photonics phase modulator approaches based on carrier injection
  - Nonlinear Optics
  - Opto-mechanics
  - MEMS based approaches
  - Plasmonics → Speed, form factor, and power handling

- FBAR approach → Small displacement will be resonantly enhanced optically and mechancially
  - Low V_π
  - High power handling
  - Relatively compact

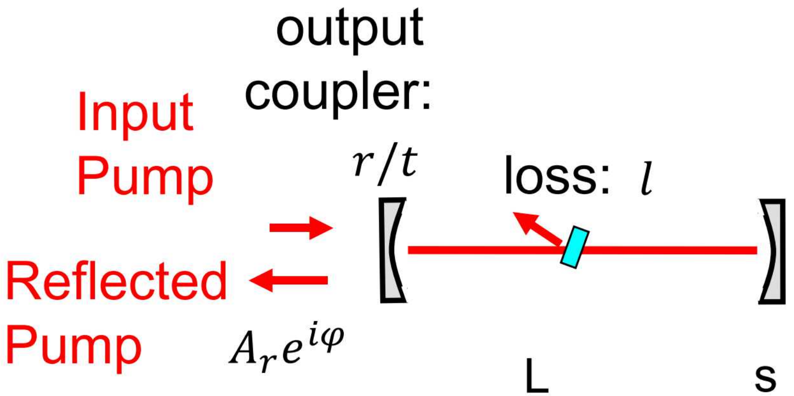
    → Narrow Band



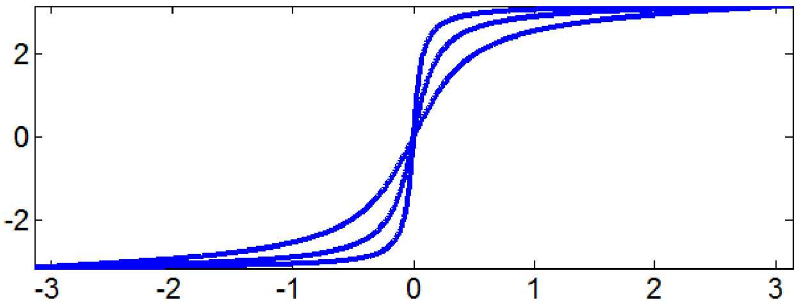
FBAR modular Phase Response

- System response is determined by the optical phase response and the FBAR response

$$\frac{d\theta}{dV} = \frac{d\varphi}{ds} \times \frac{2\pi}{\lambda}\frac{ds}{dV}$$



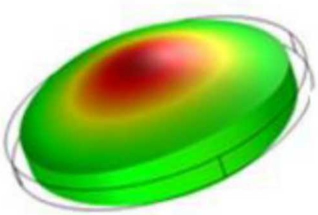
- Optical phase response



$$r_{refl} = r - \left(\frac{t^2(1-l)^{.5}\exp(i\varphi)}{1 - r(1-l)^{.5}\exp(i\varphi)}\right)$$

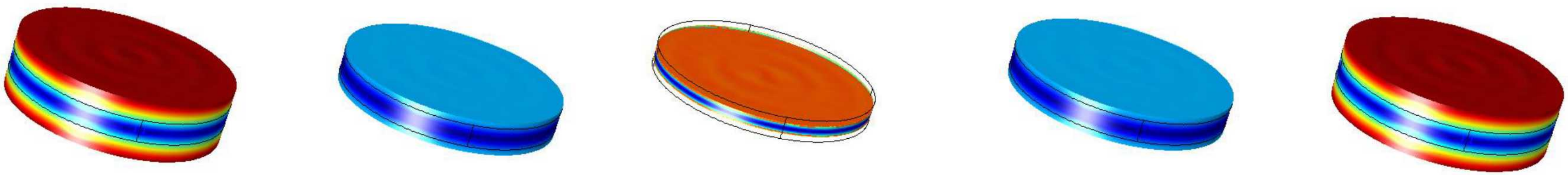
$\frac{d\varphi}{ds}$ Is determined by optical finesse

- Mechanical Displacement
  - Dilatational mode
    - → Frequency set by film thickness
    - → Displacement set by K_t^2 and mechanical Q

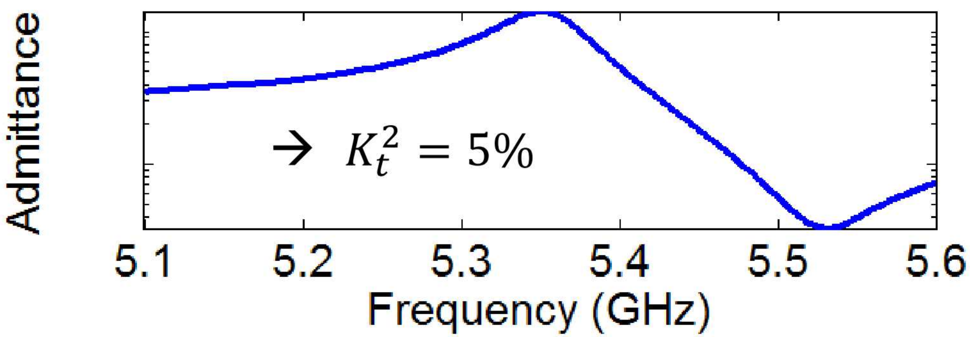


- **Optimal response with large optical finesse and mechanical Q**

FEM Simulation of FBAR Response



- Resonant frequency for dilatational mode is set by film thickness



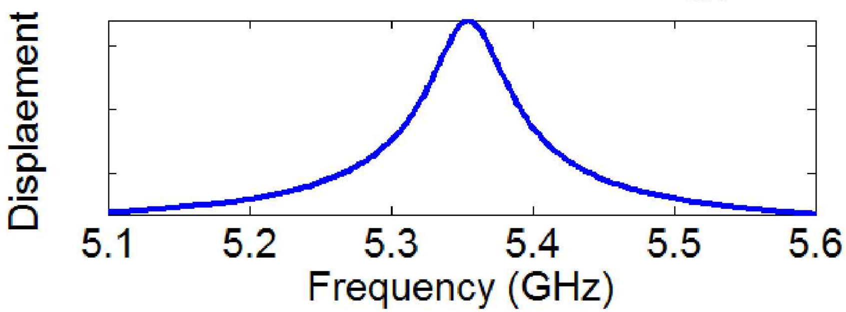
Electro-mechanical coupling

$K_t^2 \rightarrow$ determined by series and parallel resonances

Quality factor

$Q \rightarrow$ Needs to be low to have reasonable bandwidth

- The product $K_t^2 \times Q$ determines $\frac{ds}{dV}$

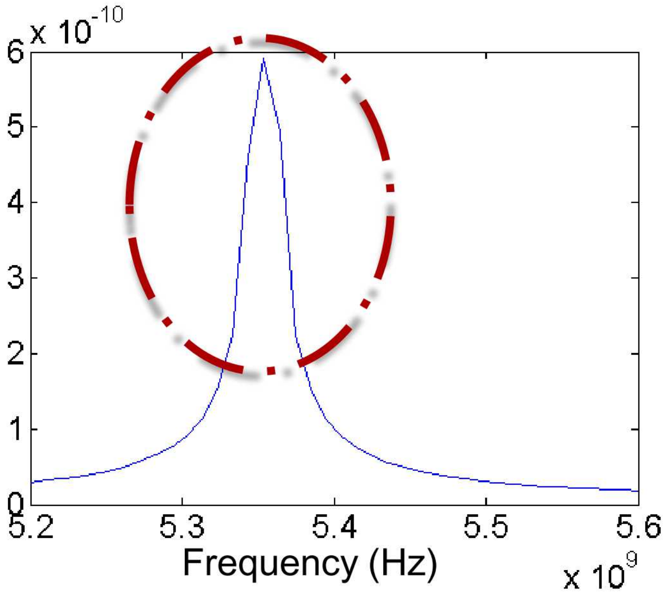


$\rightarrow \frac{ds}{dV} = .5nm/Volt$

Want large K_t^2

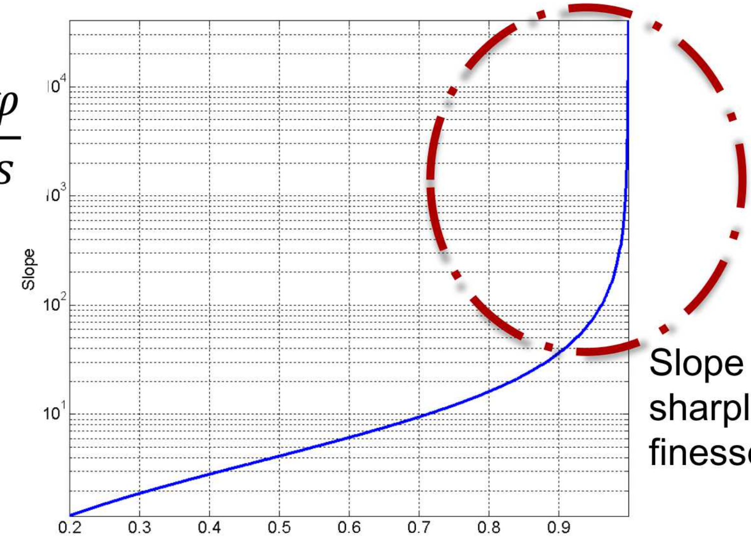
Required Optical Finesse From Model

FBAR mechanical response



$\frac{ds}{dV}$

Cavity Optical response



$\frac{d\varphi}{ds}$

Slope rises sharply with finesse

- Without Optical or mechanical Resonances V_π is large (1kV)

$$\frac{d\theta}{dV} = \frac{d\varphi}{ds} \times \frac{2\pi}{\lambda}\frac{ds}{dV}$$

.5nm/Volt

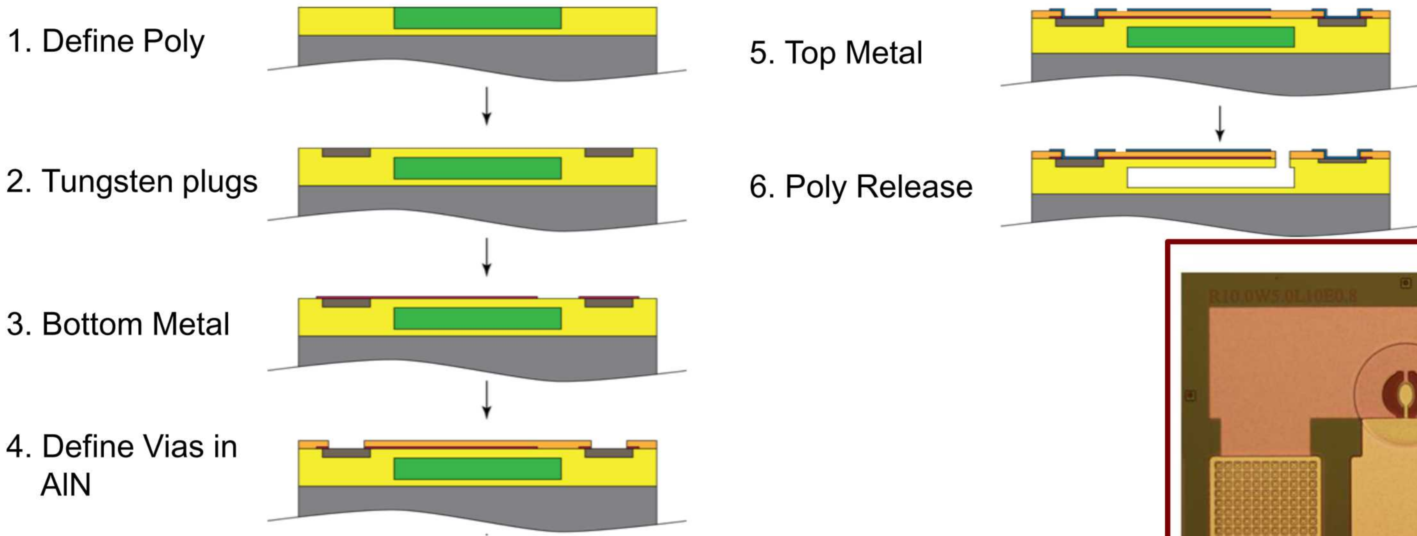
2π/1550nm

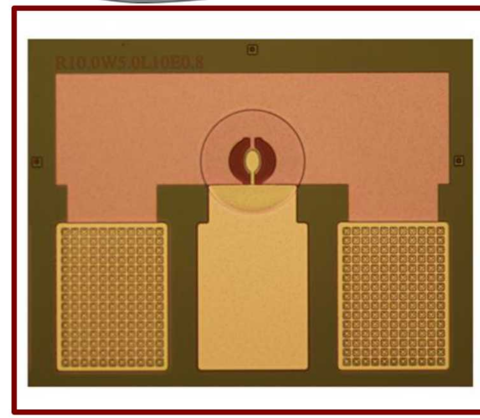
- In order to achieve a V_{pi} on the order for 1Volt

$\frac{ds}{dV}$ → Need high mechanical Q ~100 to have reasonable bandwidth

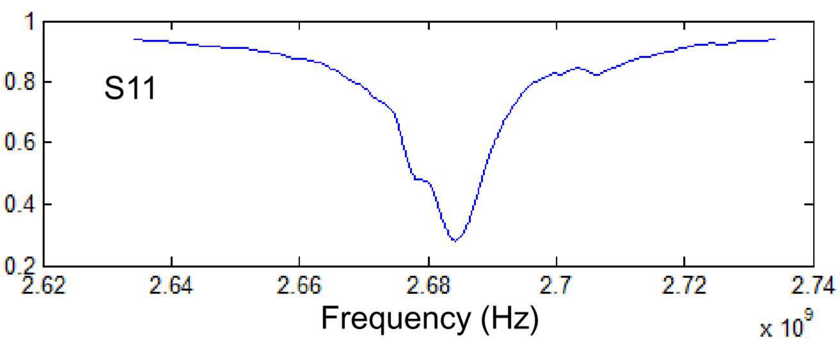
$\frac{d\varphi}{ds}$ → Want high optical Finesse → Slope on the order of 1000

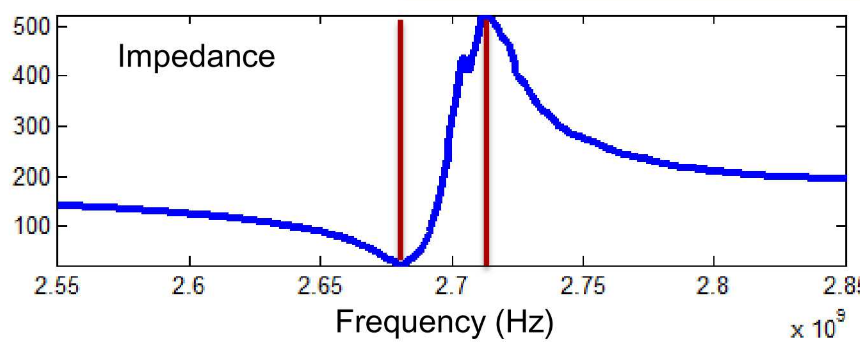
Fabrication and Electrical Characterization





- Electrical Testing Confirms Film Quality





$Q = 63$ → Targeting a bandwidth of a few percent around center frquency

$K_t^2 = 3.5\%$ → determined by series and parallel resonances

Optical Experimental Characterization

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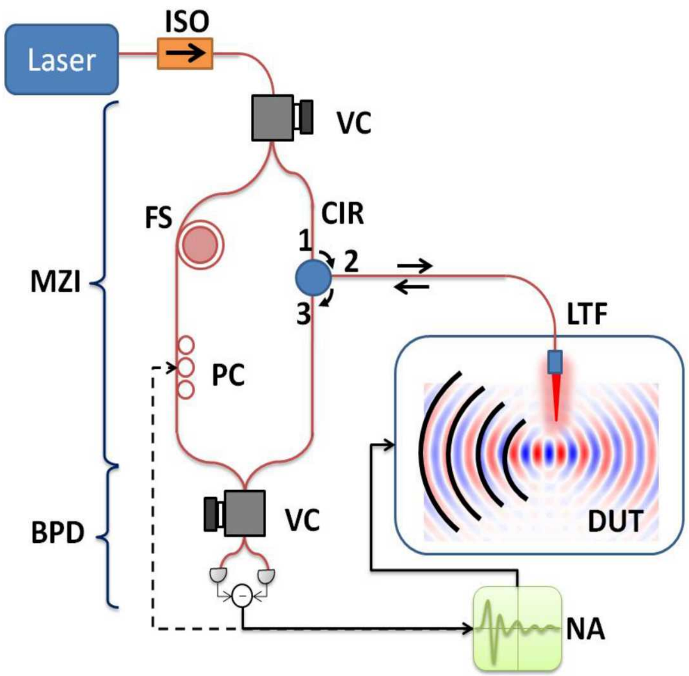
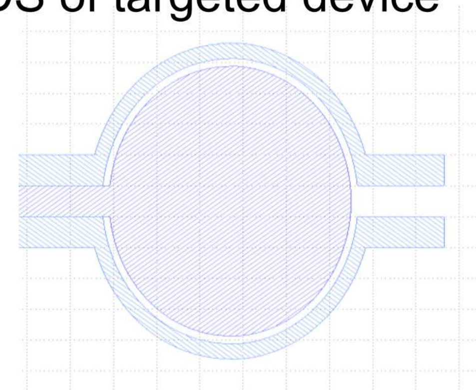
- Scanning confocal balanced homodyne interferometer for Doppler vibrometry

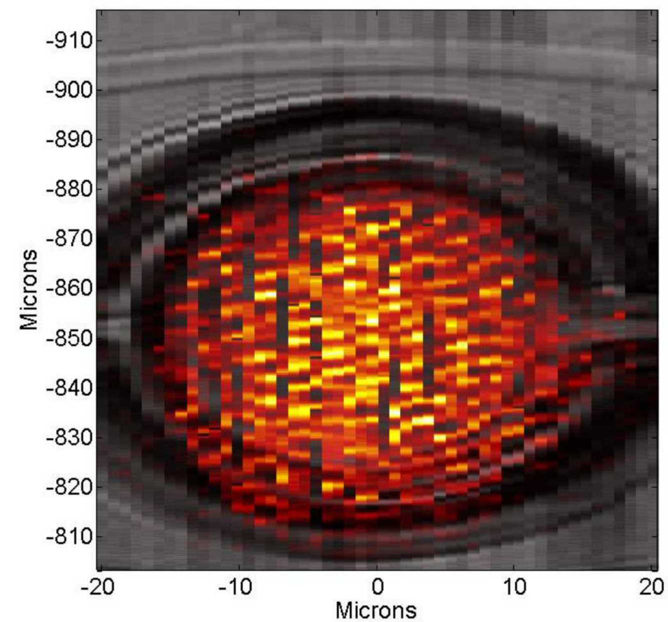


- GDS of targeted device

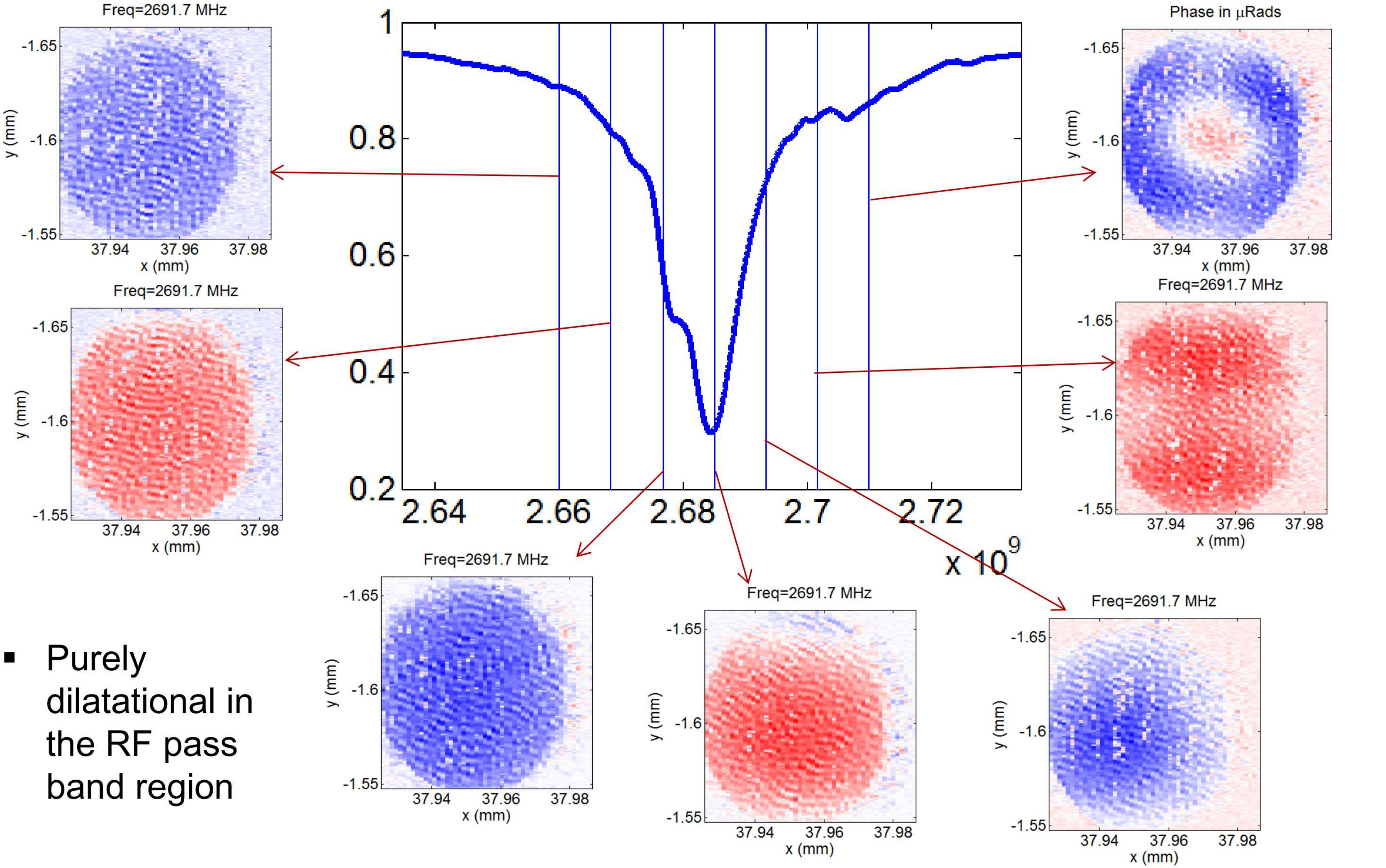


- Displacement field amplitude

Displacement field overlaid with confocal image



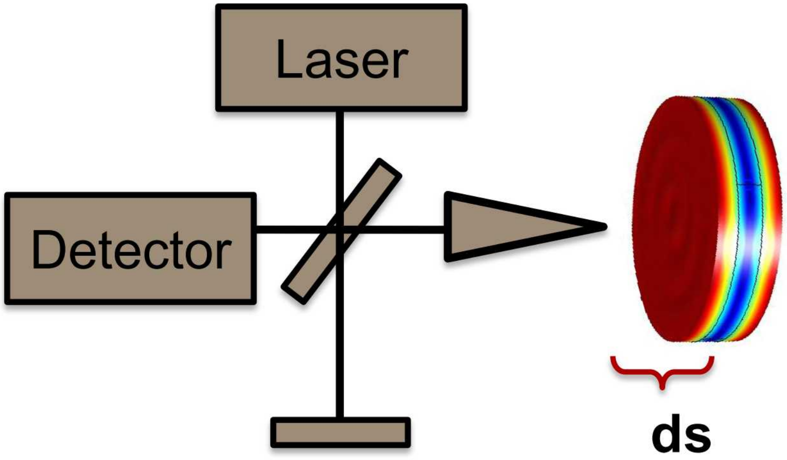
Mode Profile Across Resonance

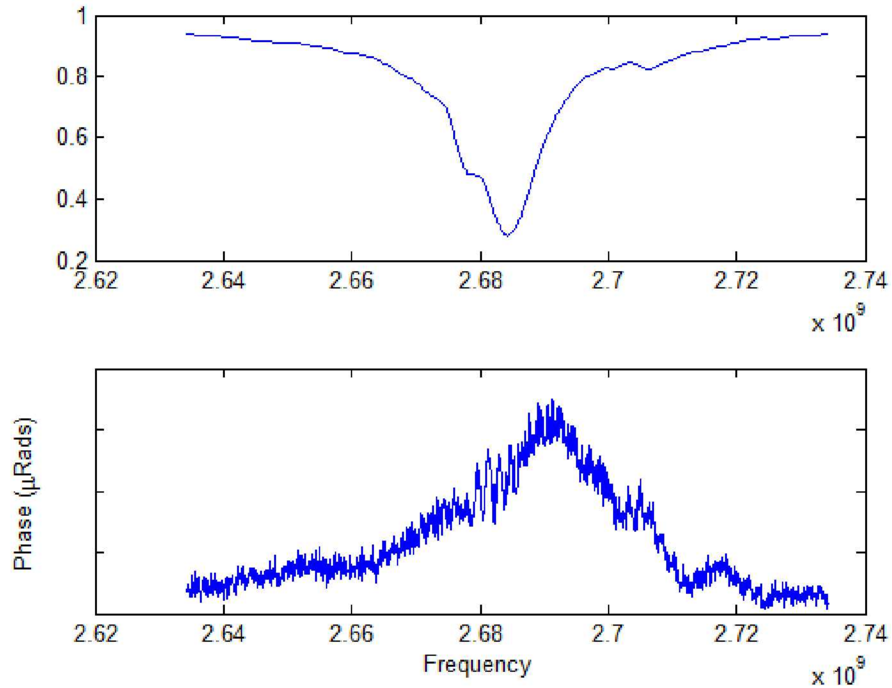


- Purely dilatational in the RF pass band region

Calibrated Phase Measurement

- Lens Taper Fiber (LTF) is positioned at center of large area FBAR





- FBAR driven with fixed RF power causing displacement amplitude, **ds**
- Detector measures dθ for a given voltage:

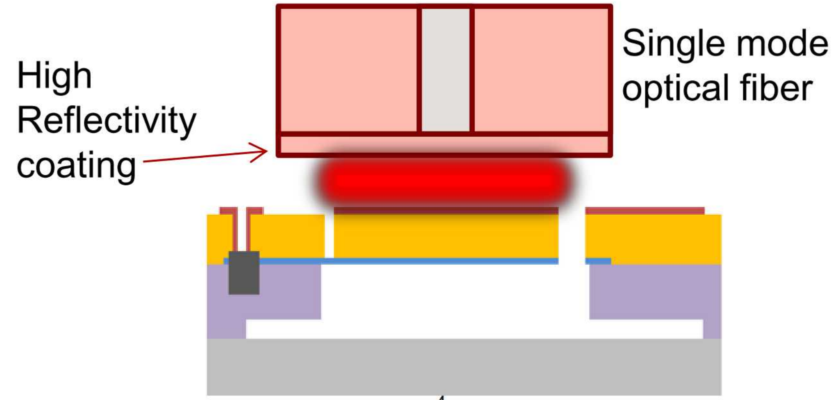
$$d\theta = \frac{d\varphi}{ds} \times \frac{2\pi}{\lambda} \times \frac{ds}{dV} \times \Delta V$$

- From these results we can determine V_π

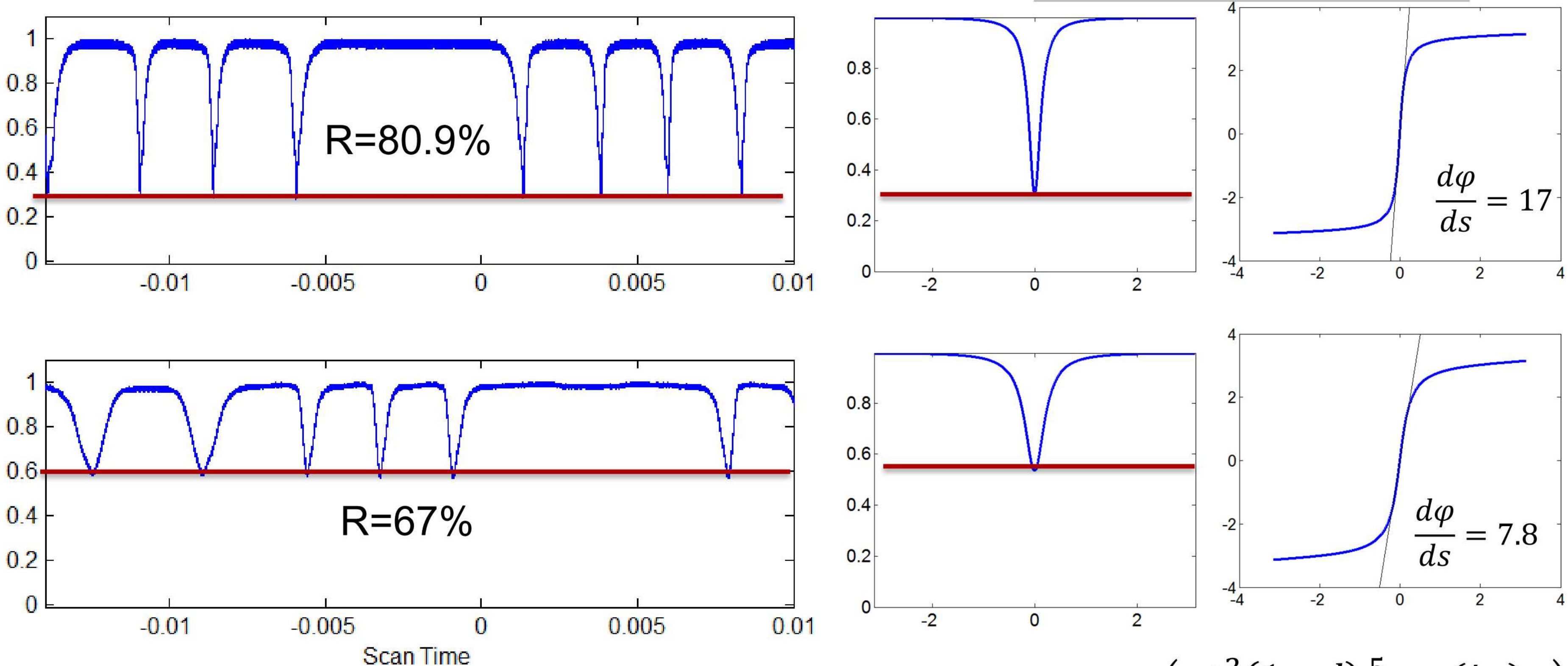
V_π = .4V / 300 μRad × π = 1.3kV

→ Optical cavity need to reduce V_π

Dielectric Coated Fiber



- Reflected power with coated fibers with different reflectivities



- Reflected power consistent with 7-8% loss

$$r_{refl} = r - \left(\frac{t^2(1-l)^{.5}\exp(i\varphi)}{1-r(1-l)^{.5}\exp(i\varphi)}\right)$$

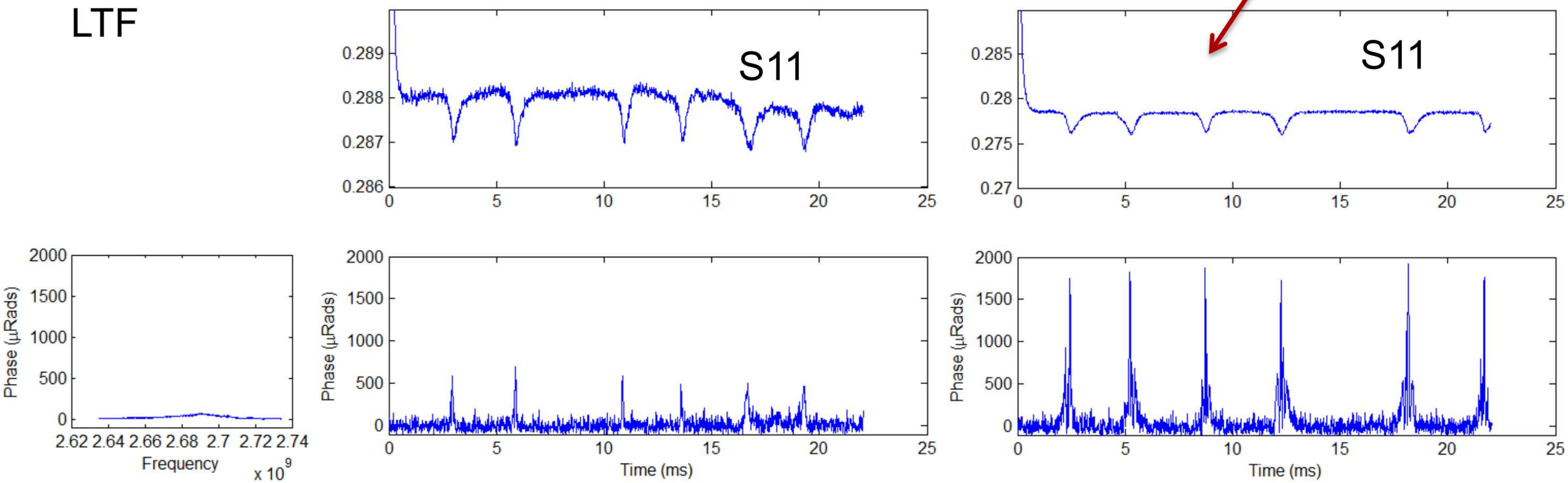
Phase Response Enhancement from Optical Finesse

Presence of cavity mode shifts Impedance

LTF

R=67%

R=80%



×1

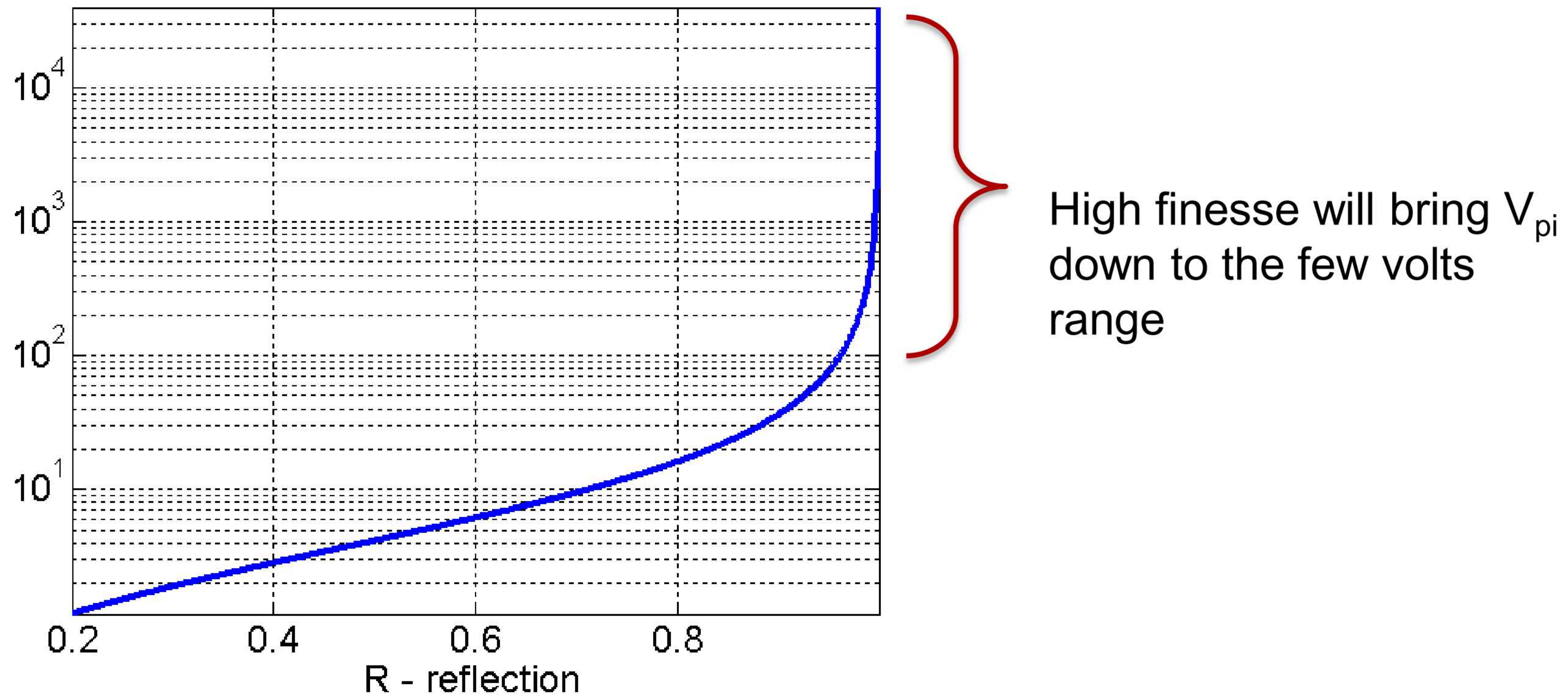
×6

×18 larger than without cavity

- Phase response increases by the optical finesse
- Reduction in V_{pi} by optical enhancement
- Driven with 5dBm RF power

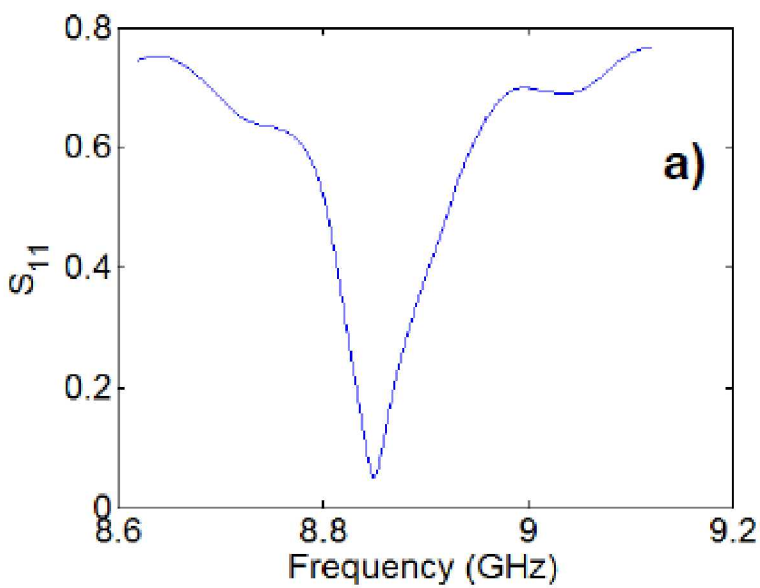
Phase Response Enhancement from Optical Finesse

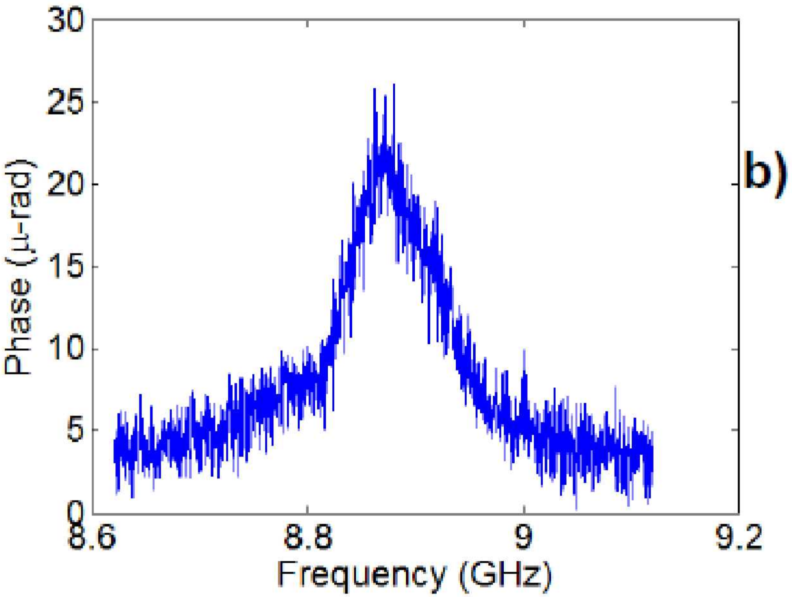
- Reduce intracavity optical loss to the .6% range



- Large improvement as finesse increases
- Improvement in mechanical Q factor
- Should get V_{π} down to a few volts

High Speed Devices

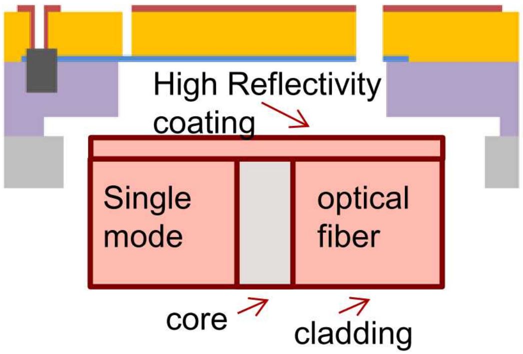




- Thinner membrane device increases resonance frequency
- of 20 μ-rad with 0dBm RF-excitation at 8.85GHz
- Finesse on the order of 1000 we expect a V_{pi} in the few volt range

Conclusion

- Proposed a way to use FBARS and a coated and cleaved fiber end to achieve high speed modulators in a Fabry-Perot configuration
- Numerically modeled system performance
- Shown that V_{pi} in the few volt range is possible given experimental parameters
- This concept has high power handling and monolithic integration, however it is narrow band.
- Improve fiber deposition quality and top metal reflectivity



Thank you