# Development of a Distributed Optical Sensor Array for Improved Subsurface Characterization and Monitoring

DE-SC0017222

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# Development of a Low Noise Optical Interrogator for Interferometric Sensing Technologies

DE-SC0017729


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U.S. Department of Energy

National Energy Technology Laboratory

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# Introduction – Why use fiber?

- Fiber Optic Sensors are much more complex than the industry standard geophone & accelerometers – Why bother?
  - EMI – Fiber is immune to electromagnetic interference. A properly designed sensing system can mitigate the 60 Hz noise problem
  - Sensing element is glass – temperature performance can push 700°C if you can pay. Typical applications can achieve 300°C. The application is restricted by the coating of the fiber, not the fiber itself.
  - No spark hazard – fiber is intrinsically safe.
  - Easy to multiplex.
  - Can be designed for high sensitivity – the response of the glass becomes a factor in the design of a transducer.

# Introduction – Two Projects

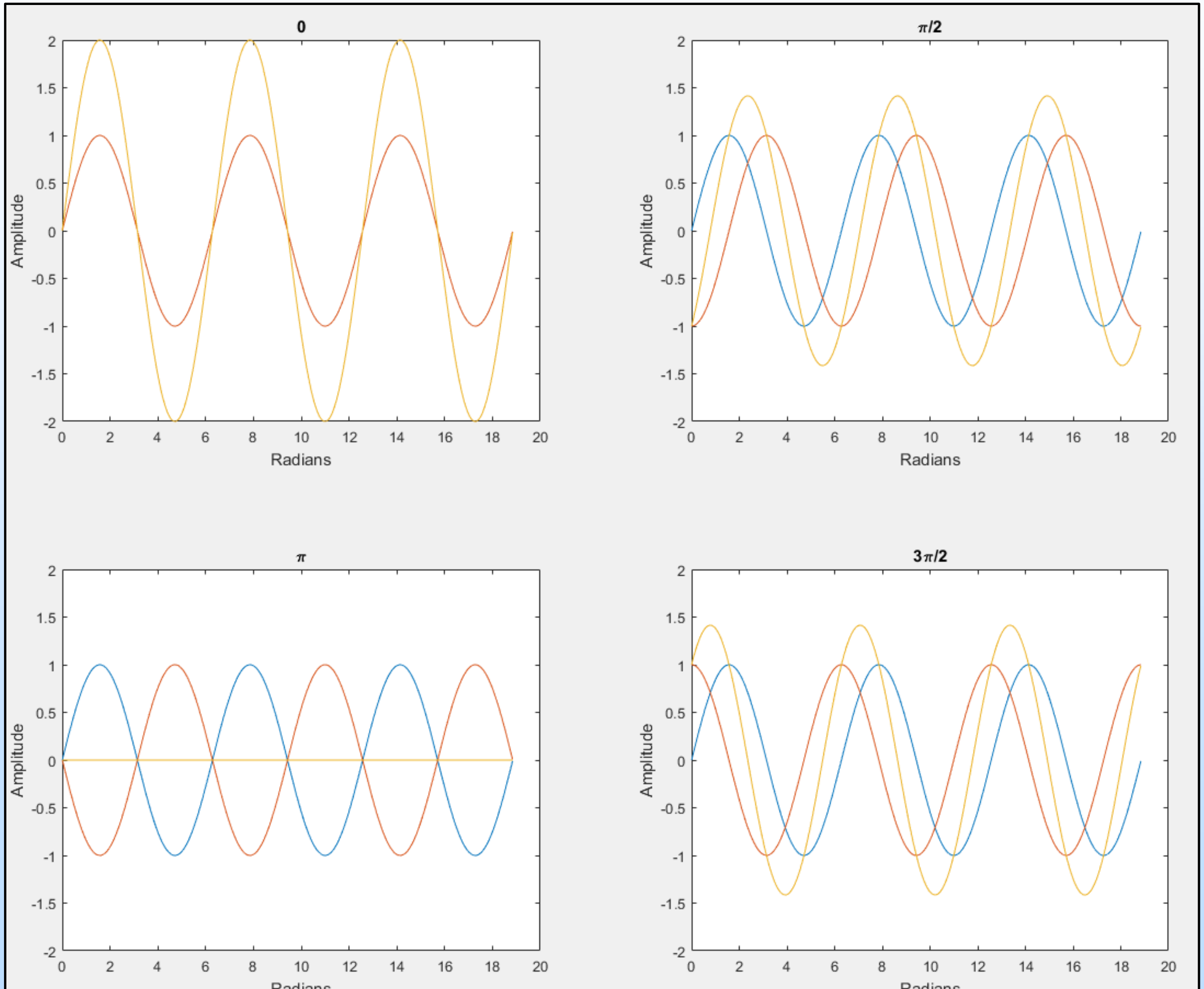
Two Projects:

- **DE-SC0017729**: Development of a Low Noise Optical Interrogator for Interferometric Sensing Technologies
- **DE-SC0017222**: Development of a Distributed Optical Sensor Array for Improved Subsurface Characterization and Monitoring

| **DE-SC0017222** | **DE-SC0017729** |
|---|---|
| ↓ | ↓ |
| Think shorter length DAS with higher Signal to Noise Ratios | Large Channel Count Sensor Arrays |
| ↓ | ↓ |
| Multiple Receivers to Lower Noise | Single Receiver; Sensor implements Mandrels |

# What is Interferometry?

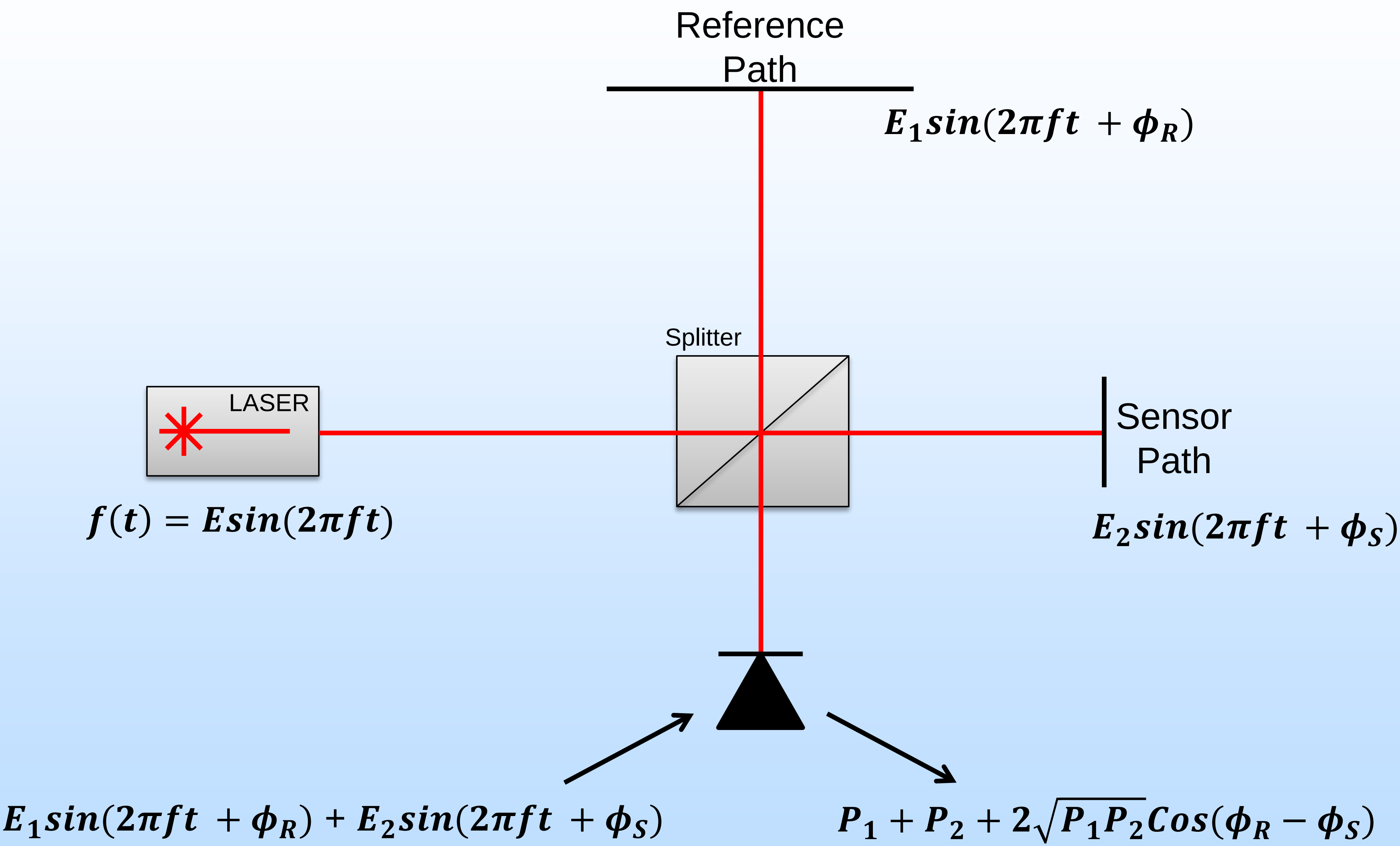
$$f_1(t) = Asin(2\pi ft) \; ; \; f_2(t) = Asin(2\pi ft + \phi) \; ; \; f_1 + f_2$$




How is this useful?

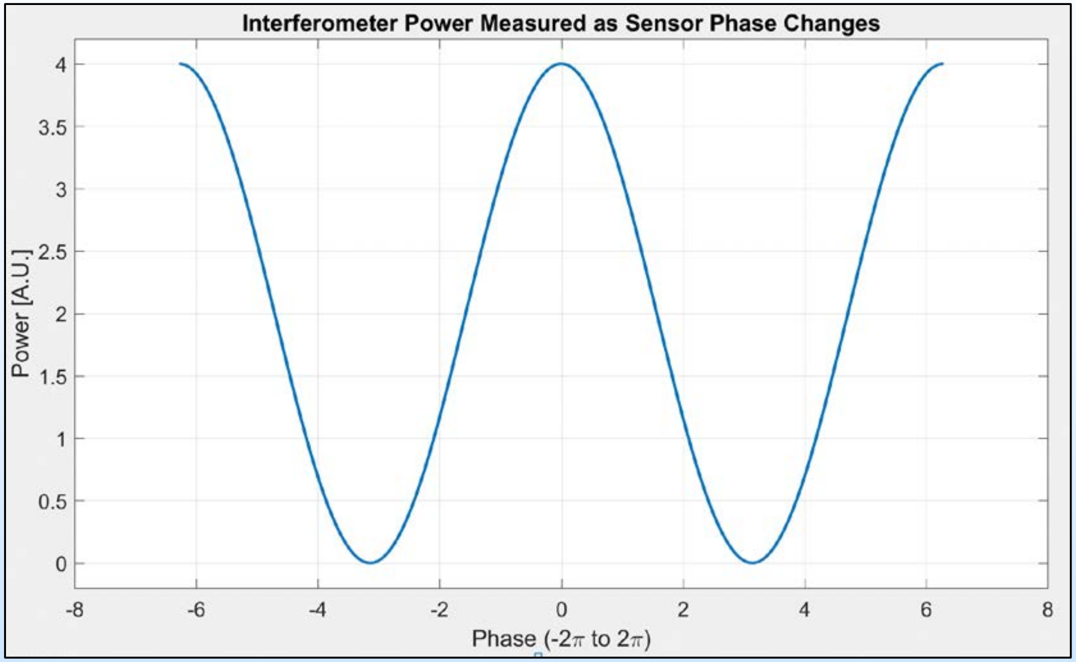
The superposition of $f_1$ and f2 tells us what φ is, so what if we could make a sensor that translates a measurand into φ?

# Interferometric Sensing



# Interferometric Sensing

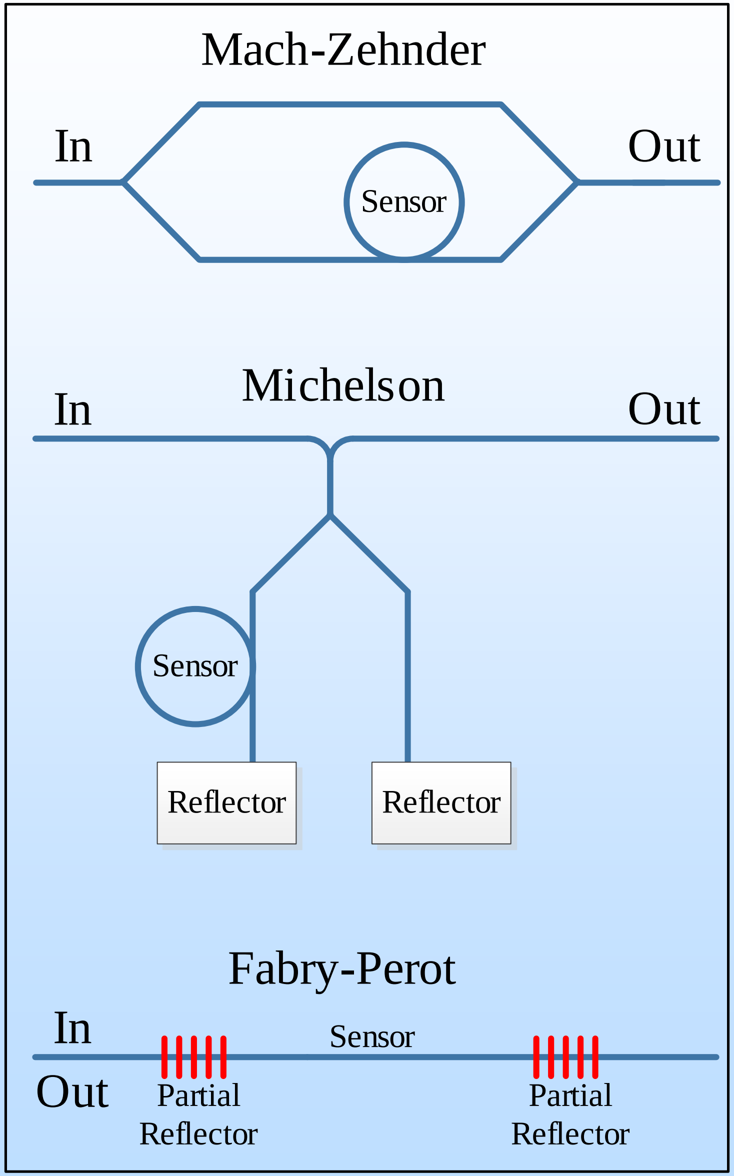
$$P = P_1 + P_2 + 2\sqrt{P_1 P_2}\,Cos(\phi_R - \phi_S)$$




Two Issues

- The measurable signal changes with phase, but the noise does not – varying SNR (+π and –π have no signal)
- Response is non-linear
- Active modulation can be used to mitigate problems

# Interferometric Sensing in Fiber




**Mach Zehnder**

- Lowest Noise, Temp max 300°C, Requires 2 fibers

**Michelson**

- 2nd Lowest Noise, Temp max 150 °C, Requires 2 fibers and 2 mirrors.

**Fabry-Perot**

- Highest Noise, Temp Max 700°C, Requires 1 fiber and Fiber Bragg Gratings (FBGs) for many sensors.

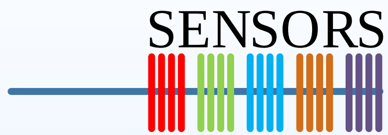
Choosing the best architecture requires analyzing the tradeoffs between:

- Noise
- Measurand & Transducer
- Packaging space
- Money

# Interferometric Sensing

- A few examples of sensing solutions
  - Hydrophone arrays
  - Borehole Vector Sensors (Vibration)
    - Surface Seismic stations too!
  - Pressure sensors (arrays)
  - Accelerometers
  - Acoustics

# Development

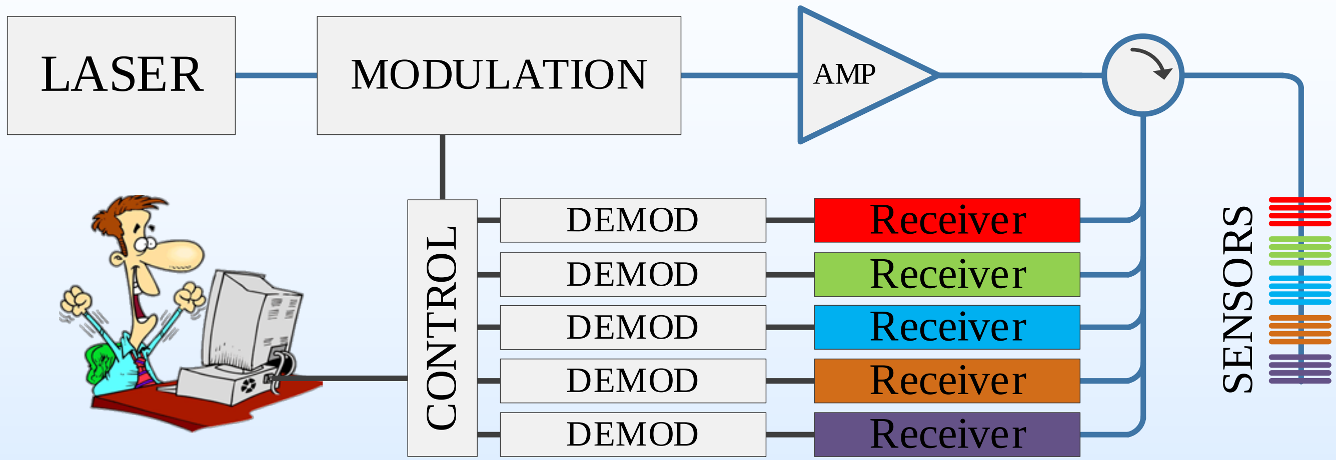



If you have a long string of reflection based sensors in a system (Time Division Multiplexing (TDM)) – the first sensor will have the lowest noise. What if we could make every sensor like the first sensor? This is the reasoning behind **DE-SC0017222**

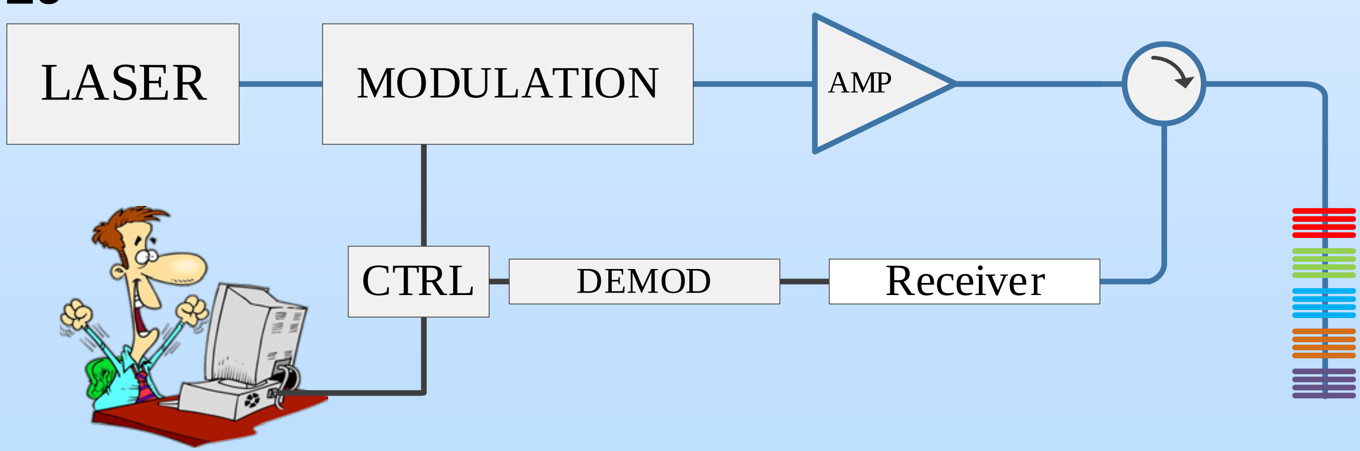
What if we can't break up the sensor responses? We still need to find a way to keep a reasonably low noise floor for all the sensors – This is the reasoning behind **DE-SC0017729**.

# Development - Design

**17222**

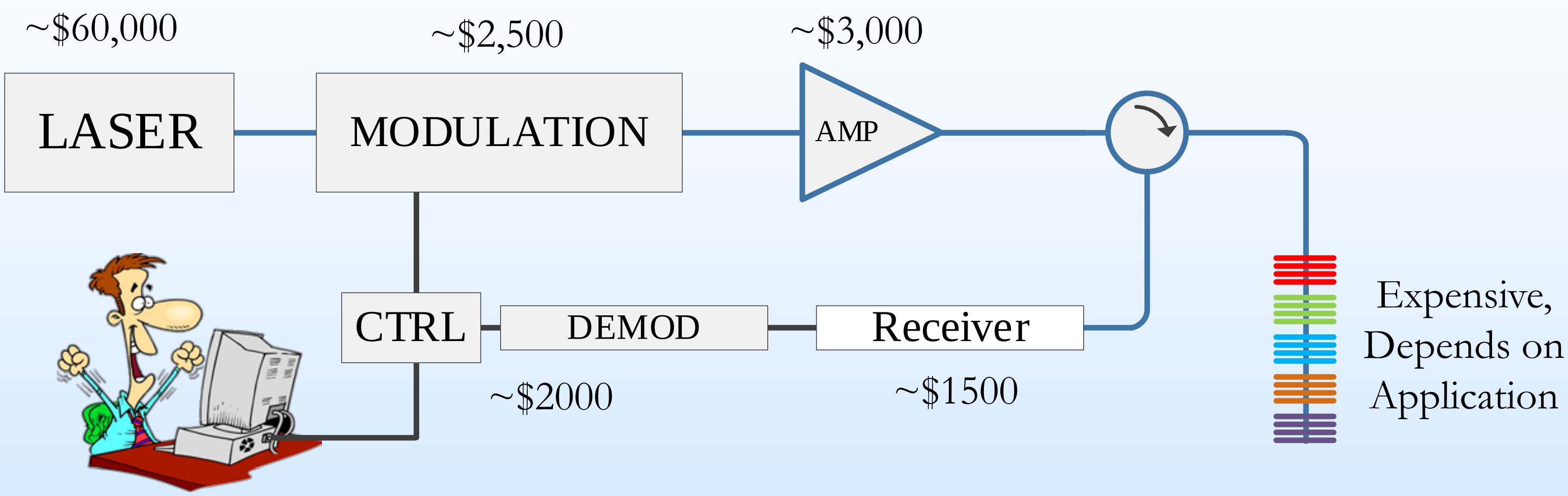



**17729**



# Development - Design

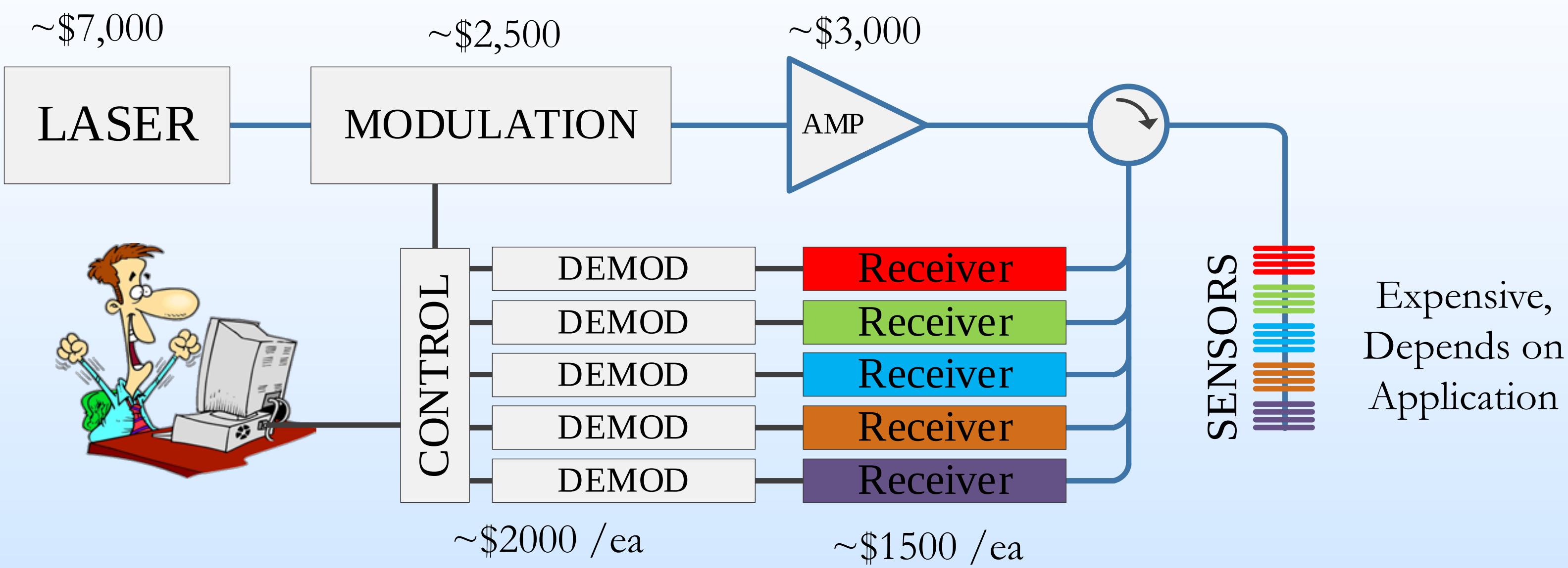
## DE-SC0017729




**Sensors will roughly cost the same same despite the interrogator implementation. For DE-SC0017729 we can see the cost is heavily loaded on the LASERs**

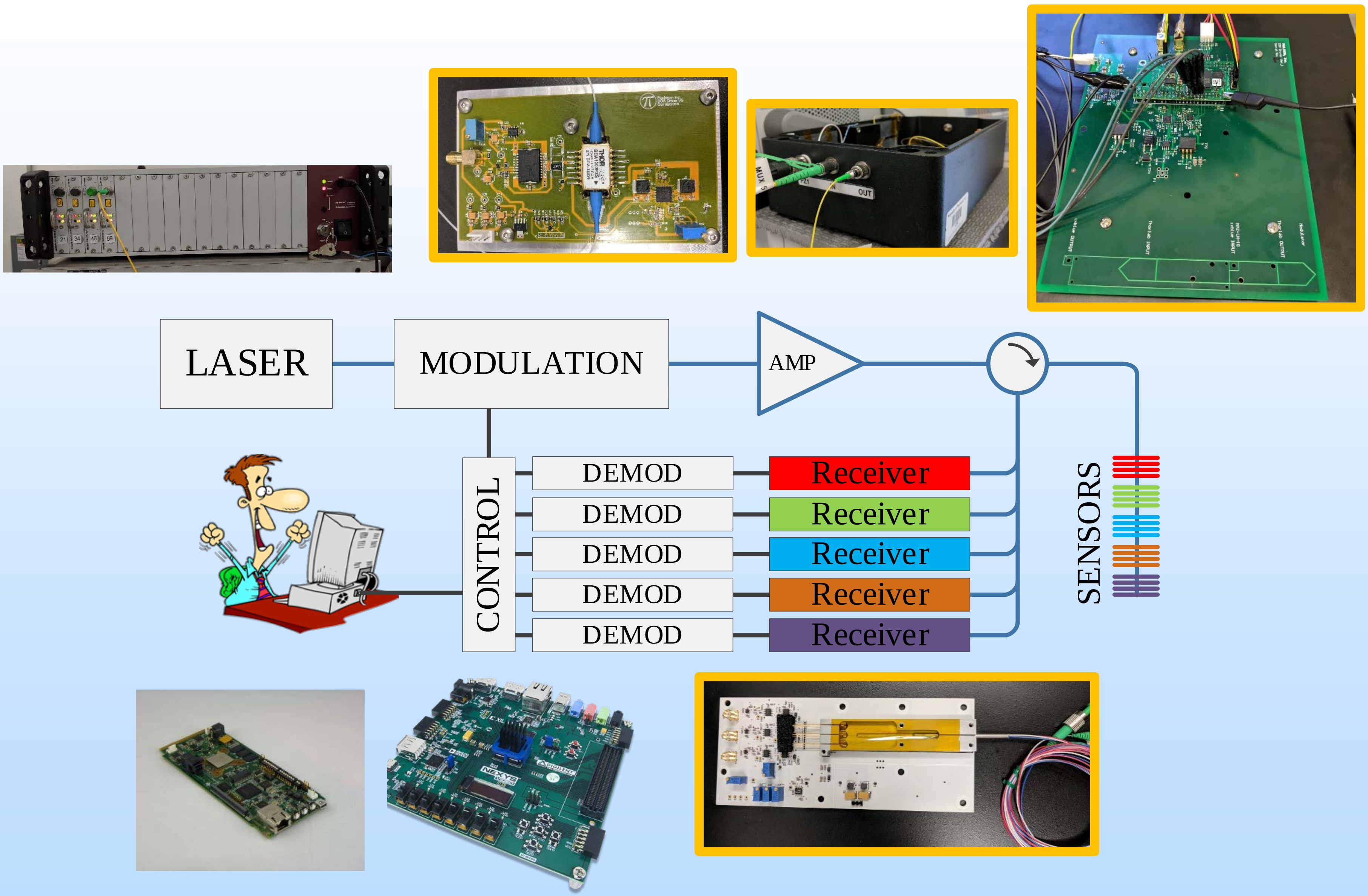
# Development - Design

## DE-SC0017222



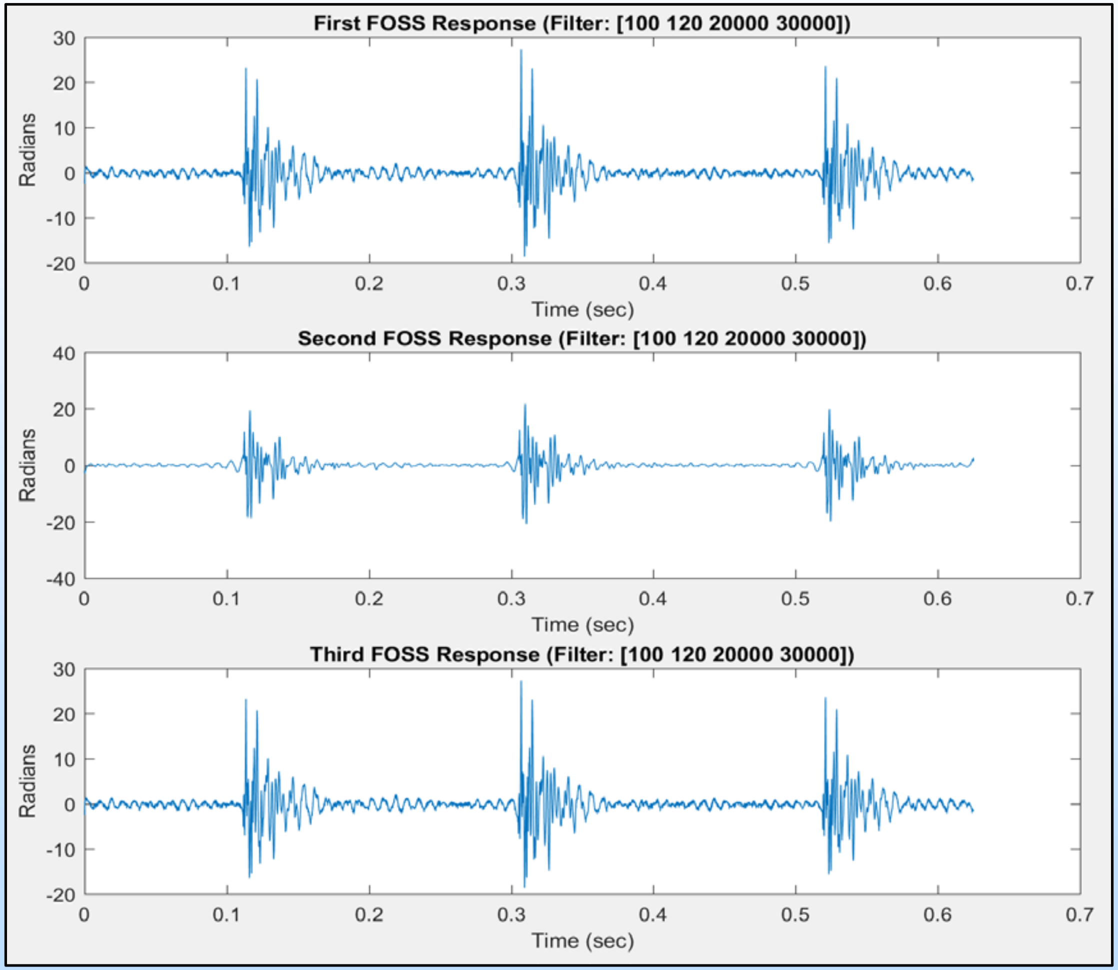

**For DE-SC0017222 the LASERs can be 10x less expensive, but more receivers are required**

# Development - Build



# Accomplishments to Date

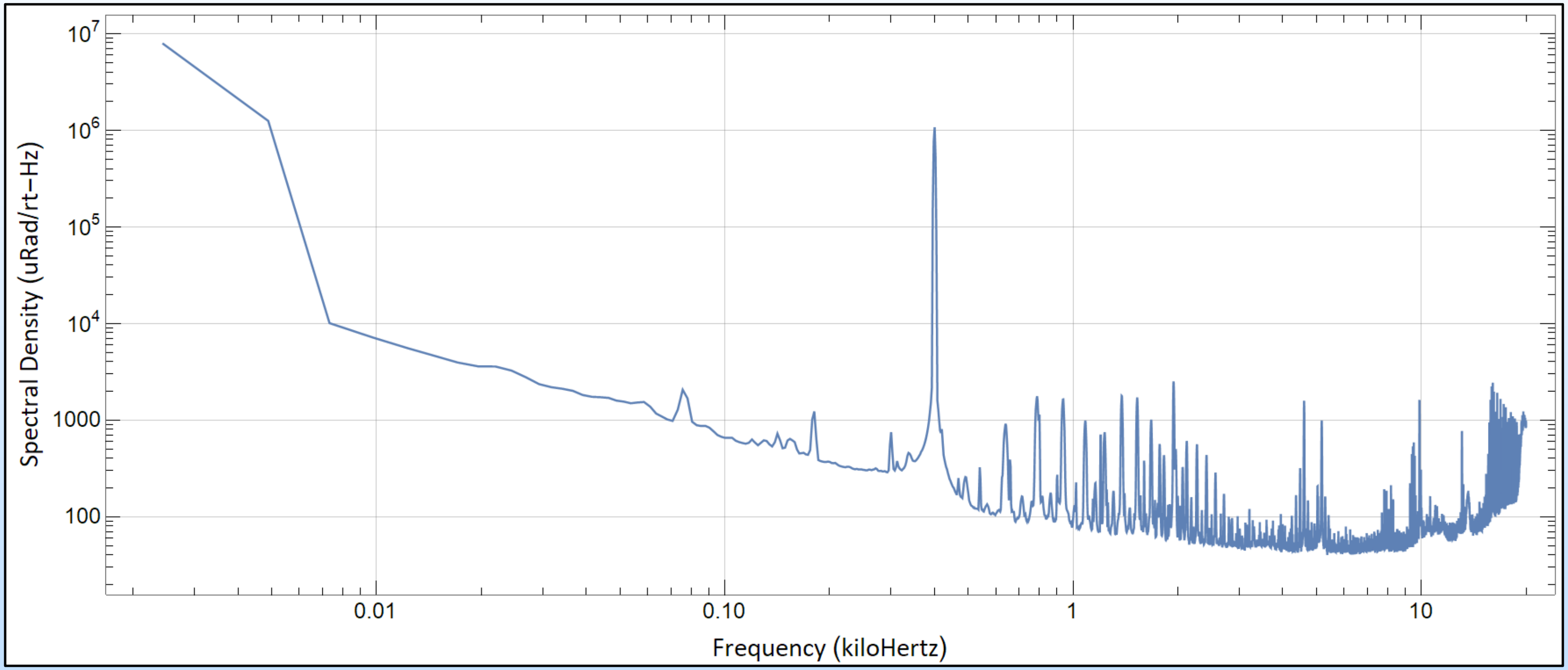
Benchtop demonstration complete (Phase I)




1-gram ball bearing table drop (2-3 cm)

# Accomplishments to Date

Benchtop demonstration complete (Phase I)




400 Hz Tone Injection – Noise Floor

# Accomplishments to Date

- Benchtop demonstration complete (Phase I)
- Full specifications developed (17729 & 17222)
- Parts, supplies and equipment ~90% acquired
- Electronics ~80% developed.
- Sensors are designed and awaiting fabrication

# Thank You!

For More Information Contact

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www.paulsson.com

# Lessons Learned

# Synergy Opportunities

– Discuss how collaboration among projects could have a synergistic effect on advancing the technologies described during the session in which you are presenting.

# Project Summary

– Both DE-SC0017222 and DE-SC0017729 are on Schedule to be completed by Q2 and Q3 respectively

# Appendix

# Benefit to the Program

- Identify the program goals being addressed.

- Insert project benefits statement.
  - See Presentation Guidelines for an example.

# Project Overview

## Goals and Objectives – DE-SC0017222

The objective with this proposal is to design a Distributed Optical Sensor (DOS) array for improved subsurface characterization and monitoring. More generally, it is to design a **cost effective** distributed sensor array that can be deployed for subsurface monitoring and characterization. Two components are required to achieve the required sensitivity:

1. A sensor string consisting of multiple sensing areas. This can be done by the in-house capabilities of Paulsson Inc. Paulsson recently acquired a Fiber Bragg Grating inscribing machine allowing for fast and cost effective prototyping of a distributed FBG based seismic array.
2. A low noise optical Interrogator. Paulsson Inc. currently has three optical interrogators, an OPD500, TDI-7000 and a CRS-3000. These units will allow cost effective testing and evaluation of the new sensors.

# Project Overview

## Goals and Objectives – DE-SC0017729

The objective with this proposal is to design an optical interrogator that is capable of being multiplexed into large sensor count arrays without impacting the noise floor while still achieving a small fiber count downhole. More generally, it is to design a low noise optical interrogator to aid in near-wellbore and far-field fracture diagnostics. Two components are required to achieve the objective:

1. An optical sensor that inherently rejects environmental noise such that an accurate measurement of interrogator noise floor can be achieved without a significant investment into an anechoic chamber and vibration isolation stations. The ideal candidate is a differential push-pull Michelson interferometer; this sensor will reject common-mode noise and any disturbances due to temperature drifts. This can be done by the in-house capabilities of Paulsson Inc. Paulsson has the fiber-optic winding machines, length meters, and optical equipment to create optical interferometers.

2. A low noise optical interrogator that can be multiplexed into a high channel count system, referred to in a single implementation as PI-SCI (Paulsson Inc – Single Channel Interrogator). Paulsson, Inc. currently has funding to develop a mandrel-less sensor string and a simple interrogator beginning in February 2017 (Proposal Number: 0000227763). This proposal is for developing a replacement for the OPD500 interrogator, while the previous project is for replacing the TDI-7000 interrogator. The two units are different and are based on different interrogation methods.

# Organization Chart

- Describe project team, organization, and participants.
  - Link organizations, if more than one, to general project efforts (i.e., materials development, pilot unit operation, management, cost analysis, etc.).
- Please limit company specific information to that relevant to achieving project goals and objectives.

# Gantt Chart

| DE-SC0017222 | 2018 | | | 2019 | | | | 2020 |
|---|---|---|---|---|---|---|---|---|
| | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 |
| **Specificaion** | | | | | | | | |
| **Interrogaor** | | | | | | | | |
| Design | | | | | | | | |
| Manufacture | | | | | | | | |
| Test | | | | | | | | |
| **Sensor** | | | | | | | | |
| Design | | | | | | | | |
| Manufacture | | | | | | | | |
| Test | | | | | | | | |
| **System Test** | | | | | | | | |

# Gantt Chart

| DE-SC0017729 | 2018 | | 2019 | | | | 2020 | |
|---|---|---|---|---|---|---|---|---|
| | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| **Specificaion** | | | | | | | | |
| **Interrogaor** | | | | | | | | |
| Design | | | | | | | | |
| Manufacture | | | | | | | | |
| Test | | | | | | | | |
| **Sensor** | | | | | | | | |
| Design | | | | | | | | |
| Manufacture | | | | | | | | |
| Test | | | | | | | | |
| **System Test** | | | | | | | | |