SAND2008-2106C

Optical monitors for high-current signal confirmation

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

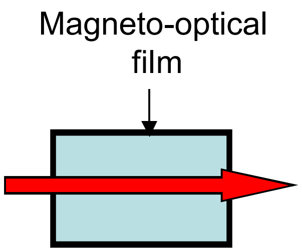
Motivation

- Monitoring of high-current signals is of interest for JTA end-event confirmation, surveillance at WETL and development and production at KCP
- Optical current monitors have several advantages over conventional current-voltage transformers including:
  - Order-of-magnitude reduction in size, weight and power
  - Immune to electromagnetic interference
  - Simultaneous high-peak-current sensing (>2kA) and high-bandwidth (>200MHz) operation
- Optical current monitors are used commercially used for monitoring ac power distribution of utilities, large systems, high power consumption

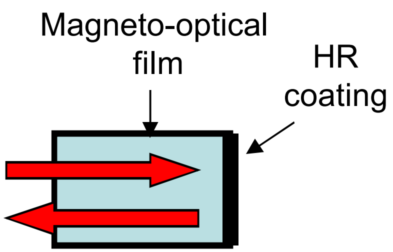
Approach

- Our goal is to develop a compact, cost-effective optical current monitor system with low-power consumption using readily available fiber-optic components from telecom industry

- Use commercially-available fiber-optic components at 1.55 μm to leverage telecom industry, reduce costs
- Design reflection-geometry sensors to reduce form factor, cabling and increase sensitivity with double-pass transmission
- Develop sensor systems with low power consumption and minimal system variability due to fiber birefringence

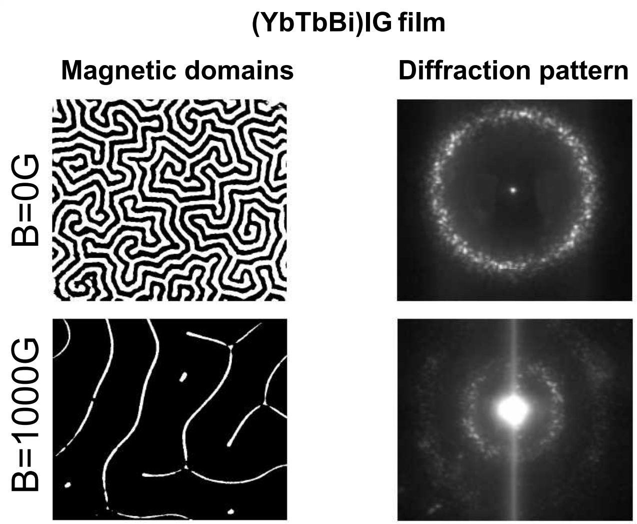


Transmission geometry

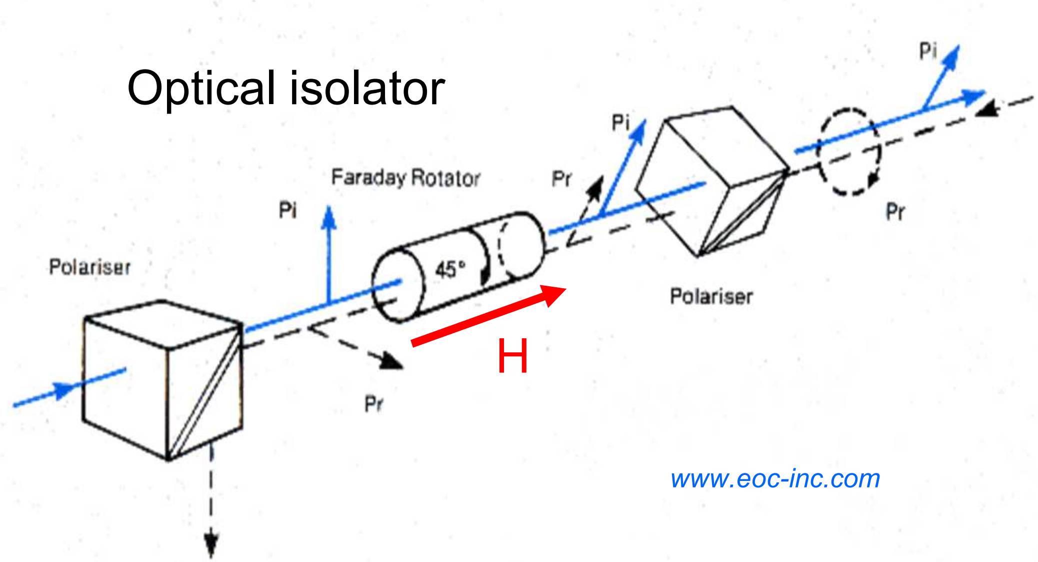


Reflection geometry

Magneto-optical materials



H. Sohlstrom, Ph.D. Thesis, RIT



- Optical current monitors to date have predominantly used the non-reciprocal Faraday rotation effect in magneto-optical crystals to measure changes in current-induced magnetic field
- Rare-earth iron garnets (RIGs) have strong Faraday rotation properties. Bismuth-doped iron garnets (BIG) and yttrium-doped iron garnets (YIG) are commonly used.
- Magnetic field vector parallel to optical axis produces Faraday rotation which generally saturates at above some magnetic field value. Magnetic field also effects light propagation and diffraction via scattering with magnetic domains.
- In general, the amount of rotation is a function of material, length and magnetic field For telecom optical isolators. a saturating magnet is used to set rotation angle.

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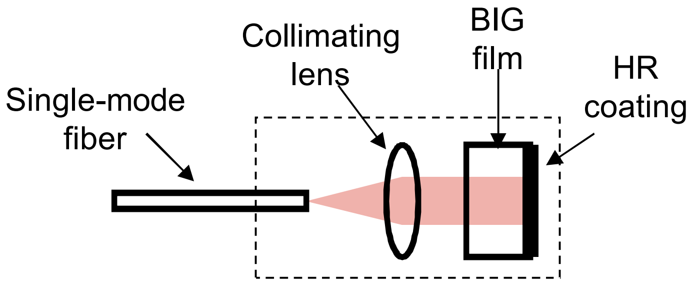
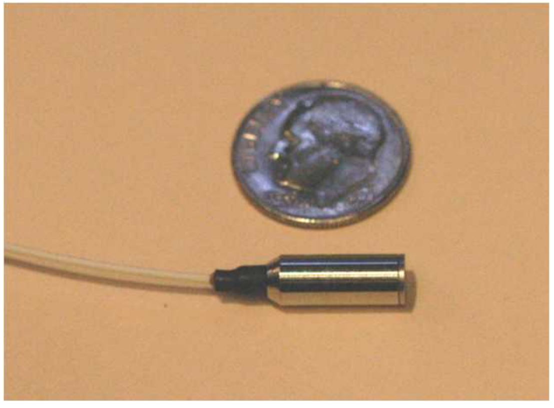
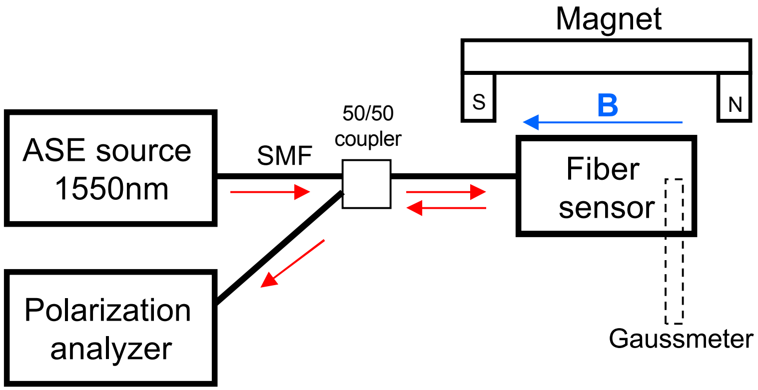
Packaged reflective optical monitor

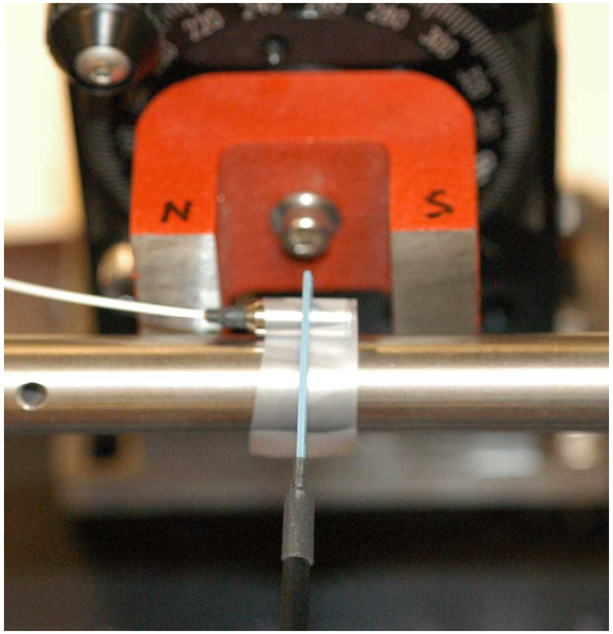




- Custom packaged sensor was fabricated to enable more flexible testing compared to free space components
- Sensor consists of aspheric lens for beam collimation and 1-mm-thick (confirm) BIG film with a high-reflectivity coating on the backside of the film
- Allows for BIG material characterization
- Can connect in-line polarizers to sensor

DC polarization analysis with magnetic field

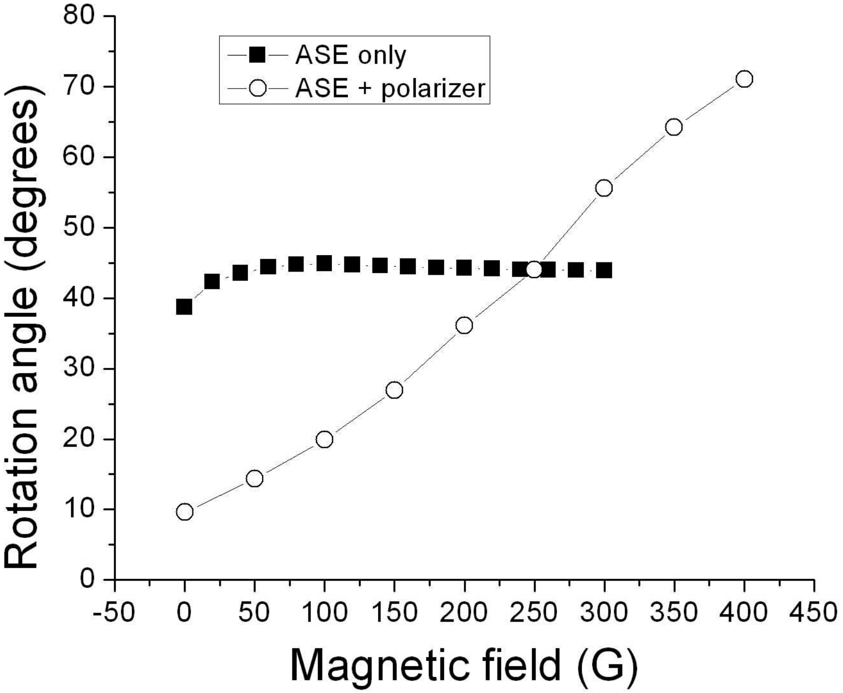




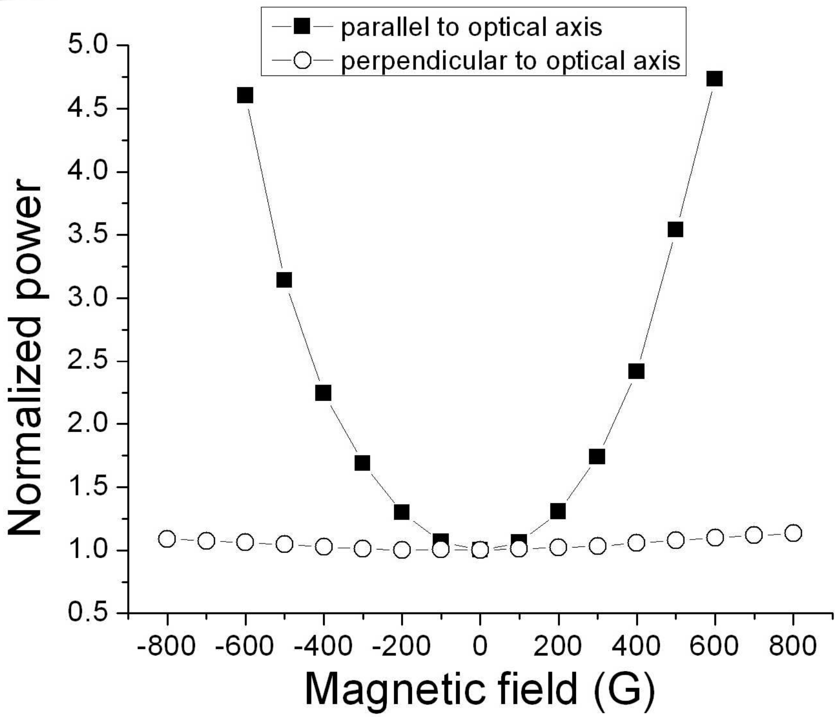
- DC measurements taken to understand magneto-optical properties of BIG film
- Distance-controlled magnet and gaussmeter used to provide and measure externally applied magnetic field
- Measured dc changes as a function of external magnetic field in the following parameters:
  - Faraday rotation
  - Power transmission
  - Degree of polarization (DOP)
- ASE output power = 8mW

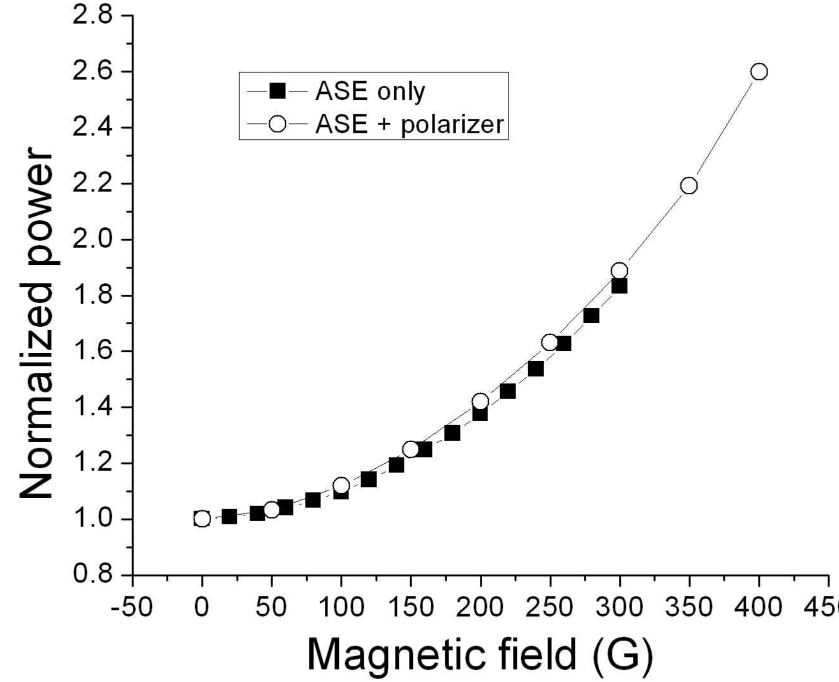
Faraday rotation

- Measured rotation angle for polarized (DOP=95%) and depolarized (DOP=5%) light input as a function of B parallel to the optical axis.
- Polarized light produced by inserting an in-line polarizer between ASE source and 50/50 coupler input
- Linear change in rotation angle for polarized light input only
- No appreciable change in rotation angle for depolarized input



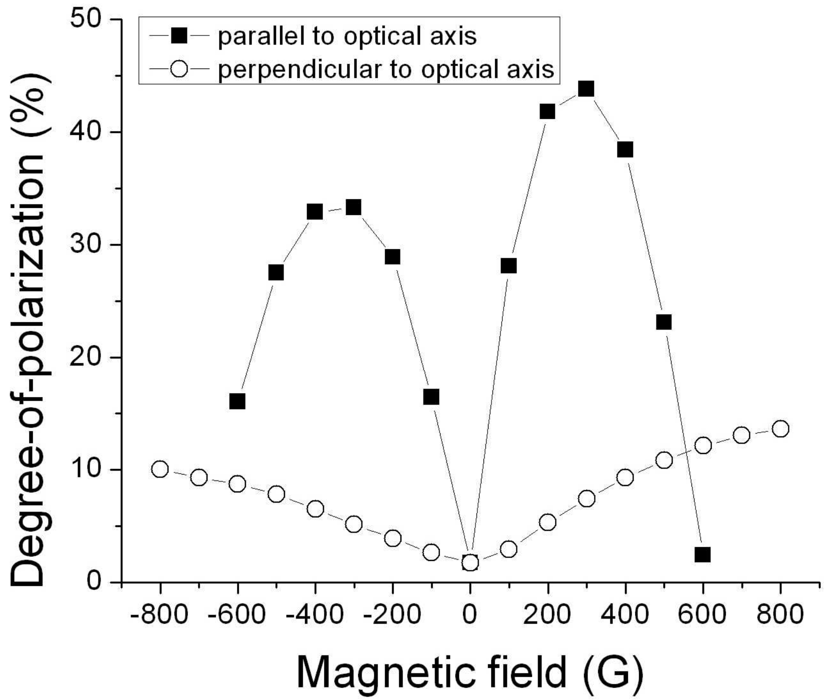
Power scattering

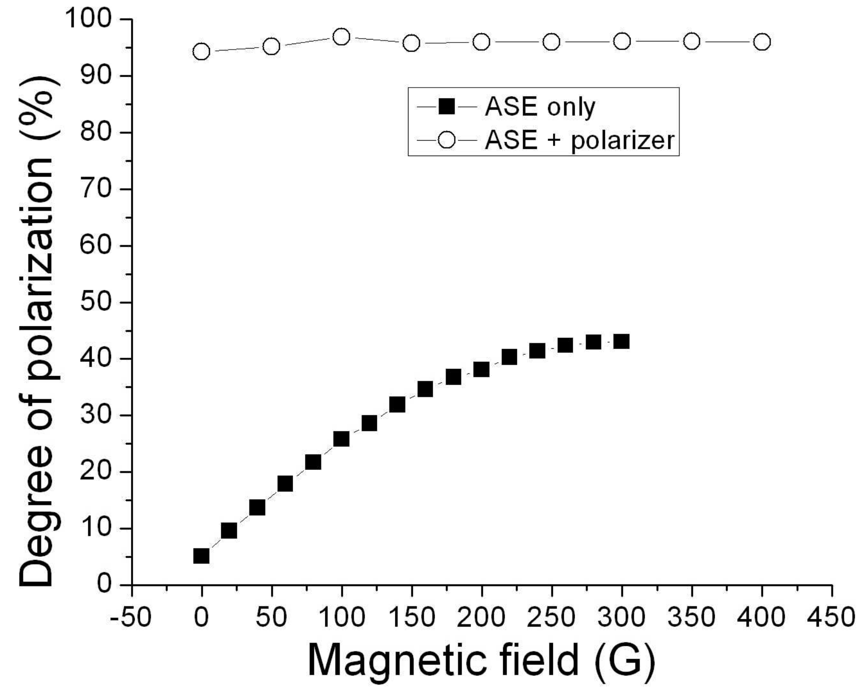




- BIG film has high insertion loss with no external magnetic field due to power scattering from unaligned magnetic domains
- Reduced power scattering observed as a function of applied magnetic field parallel to optical axis due to increasing orientation of magnetic domains
- Increase in power transmission shows H^2 dependence
- Relatively independent of input power, polarization and DOP

Degree of polarization





- Change in degree of polarization (DOP) shows periodic behavior with DOP increase as high as ~40% for magnetic field parallel to optical axis
- Increase in DOP also observed for perpendicular magnetic field
- Change in DOP not observed for highly polarized light input case

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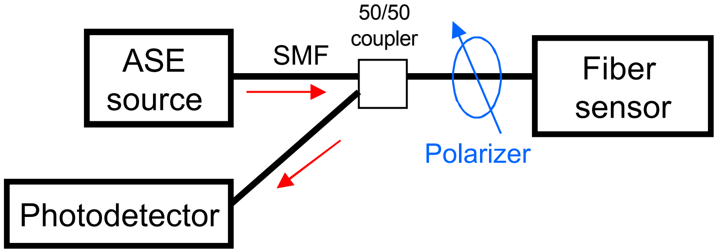
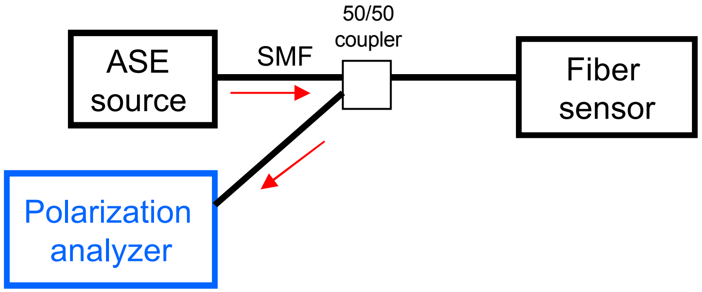
Sensor system considerations

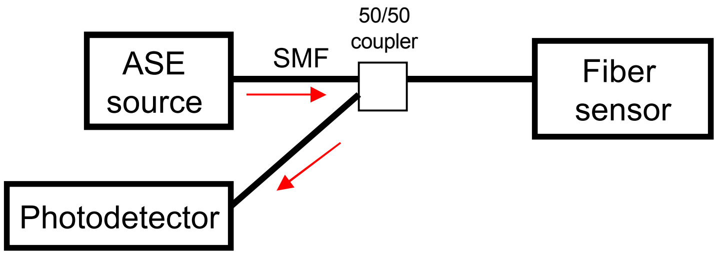
- Faraday rotation mode (standard)
  - Linear response
  - ~10-20dB insertion loss from polarizers necessitates higher source power



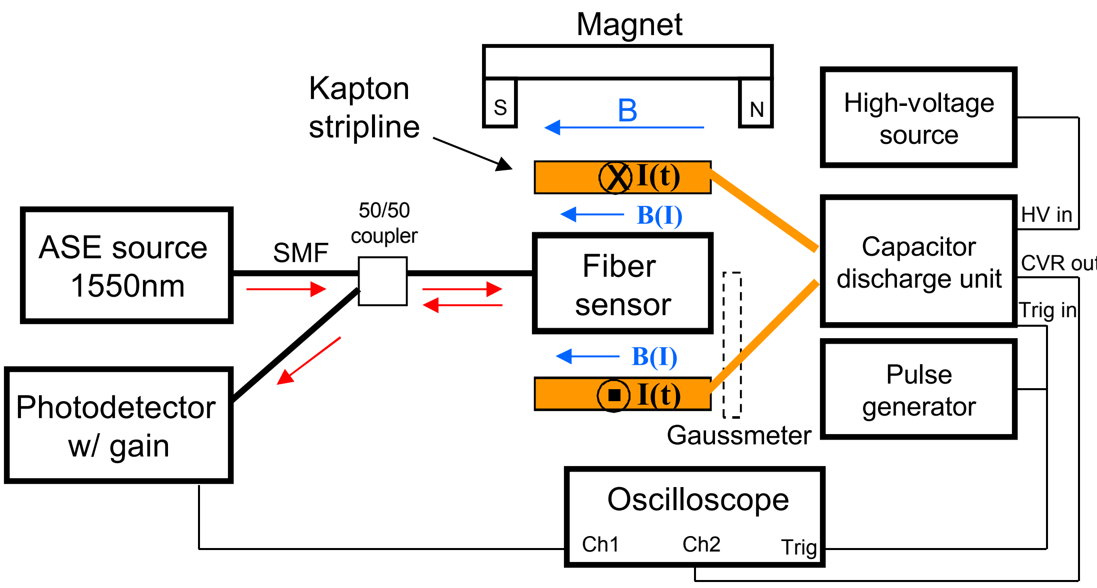
- DOP mode (new)
  - Power and polarization independent
  - High-speed polarization analyzer required, limited sensing range



- Power scattering mode (new)
  - Simplest configuration
  - Non-linear response

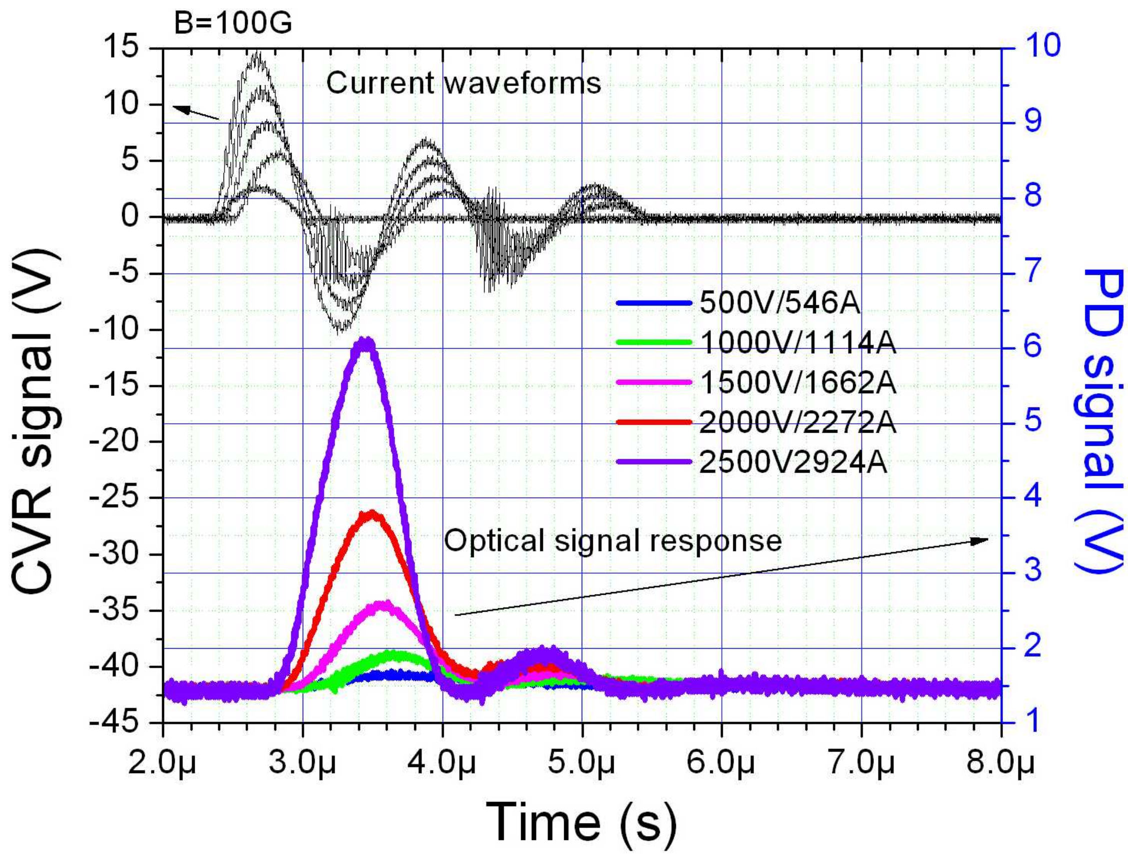


Transient current pulse testing



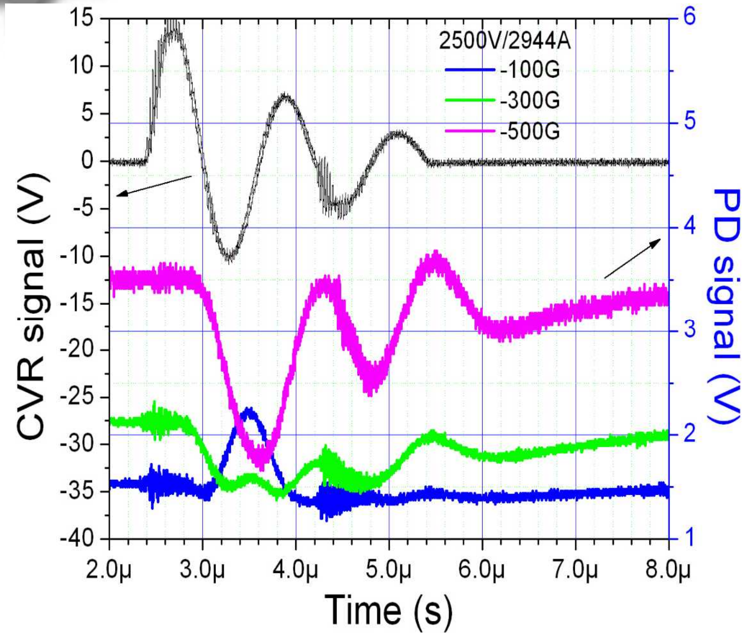
- Capacitor discharge unit (CDU) produced current pulses up from 500A to ~3kA peak current with 150-ns rise times over Kapton stripline with 10-mm-wide conductor
- Measure corresponding optical response from fiber sensor sandwiched between Kapton lines
- Also evaluate optical response as a function of external magnetic field bias

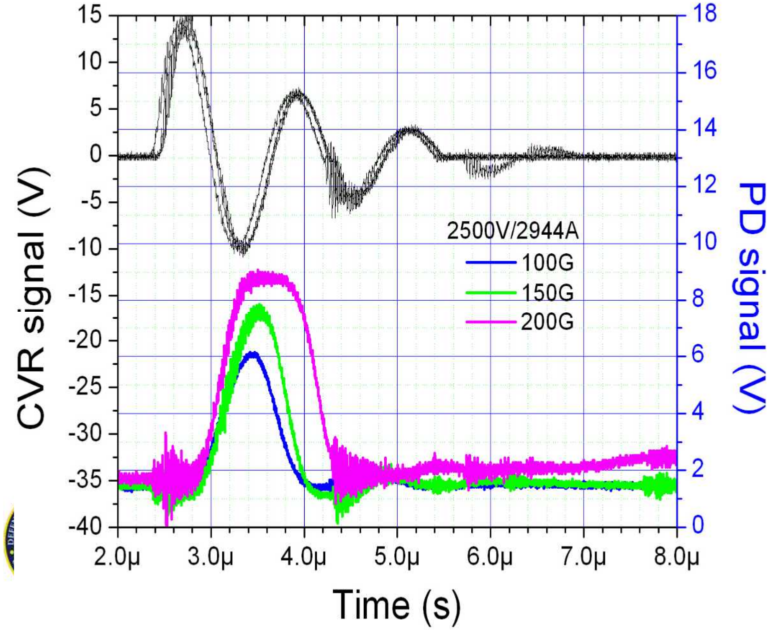
Transient sensor response

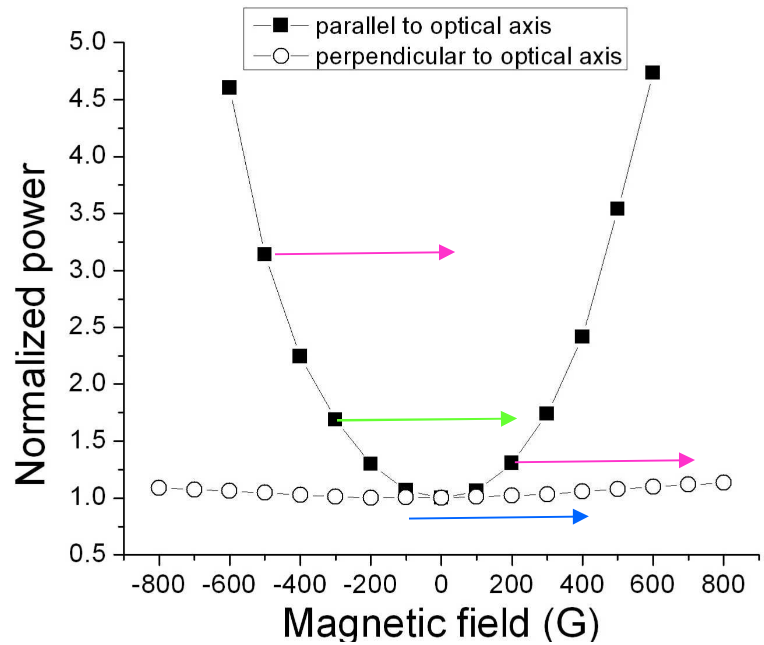


- Optical response observed up to ~2500V/3000A (limit of CDU)
- 500-ns delay between current waveform and optical response
- Slightly broader optical response, negative current swings and secondary transients not well resolved
- Measure peak signal amplitude of optical response as a function of peak current under various external magnetic field conditions

Transient response with external magnetic field







- Transient behavior vs. external magnetic field follows dc properties
- At negative B, power drop observed corresponding to current peak until current transient crosses minimum
- Estimate this sensor position in Kapton stripline at 2500V/2944A corresponds to B=~450G
- For positive H, sensor response saturates for 2500V/2900A signal for B>150-200G
- Estimate that this BIG film saturates at total B=600-650G

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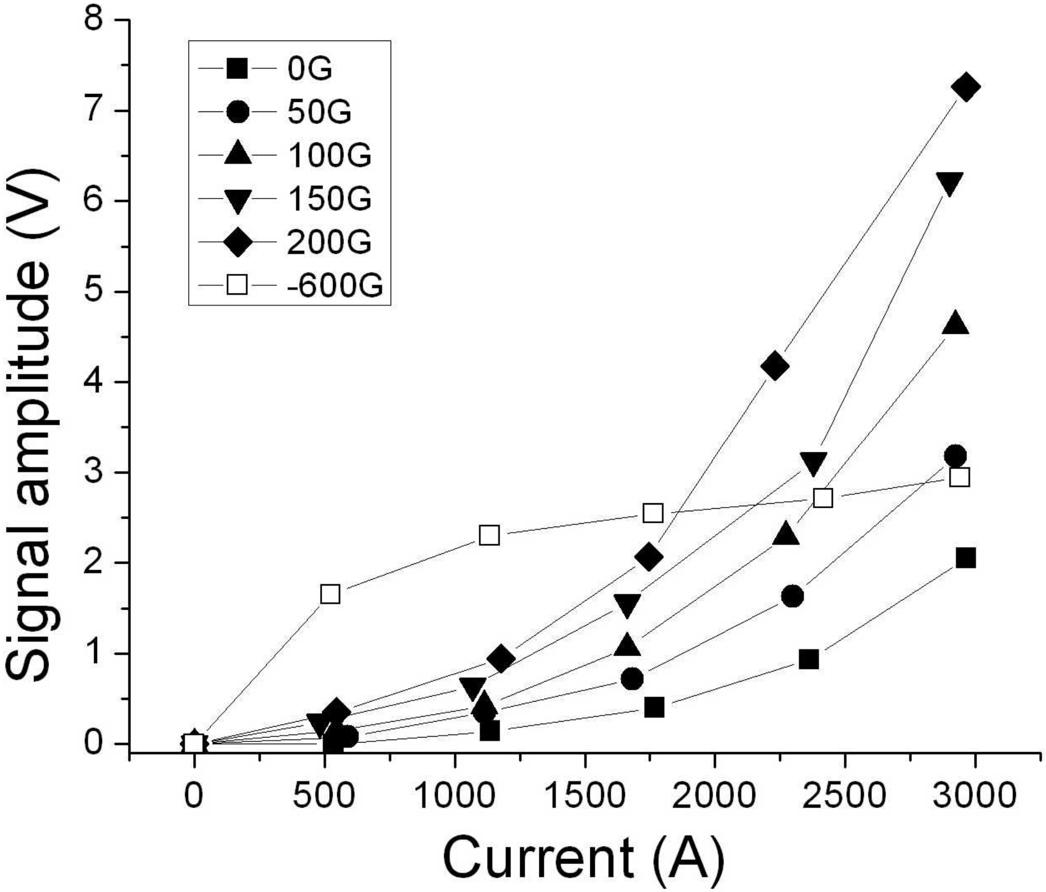
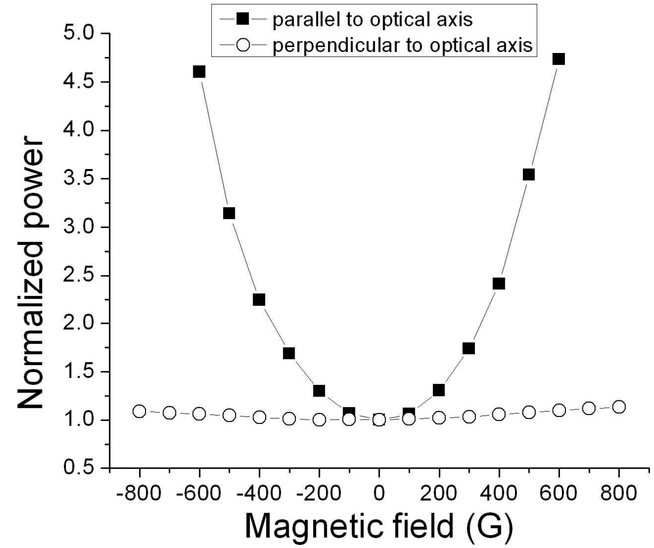
Transient sensor response summary





- Plot peak signal amplitude vs. peak current for various external magnetic field biases
- Higher positive bias increases sensitivity but decreases dynamic range
- Negative bias increases senstivitiy for lower currents
- Follows dc characteristics

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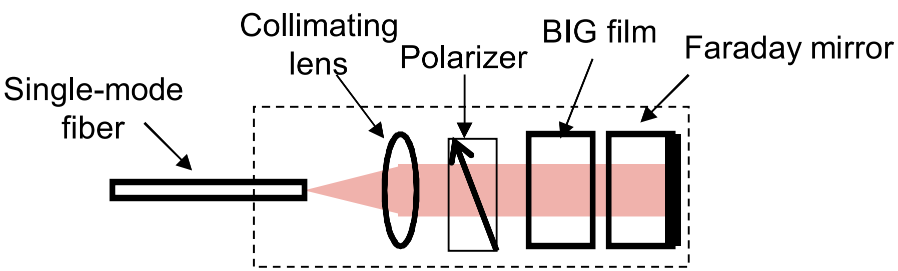
Faraday rotation optical current sensor - comparison

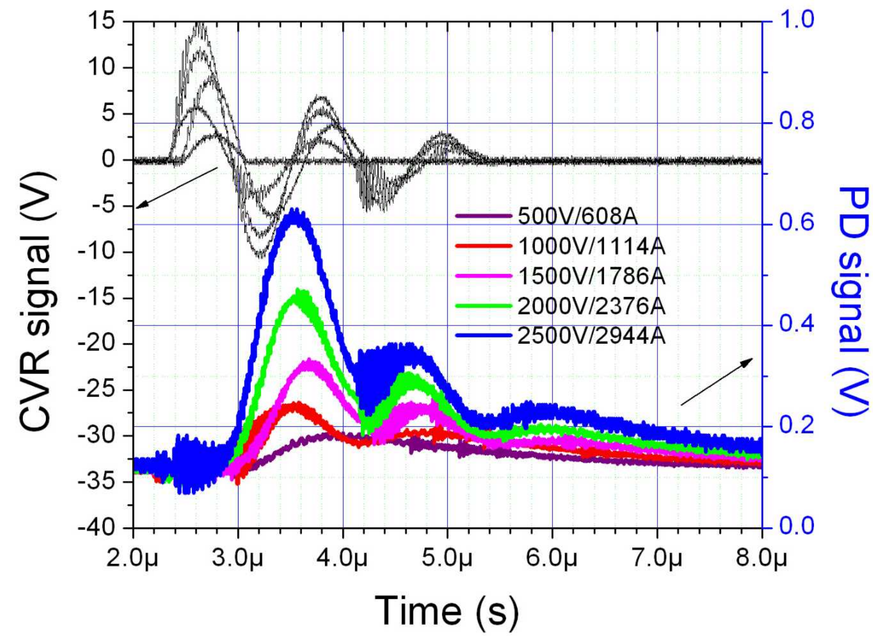
Faraday Rotation sensor

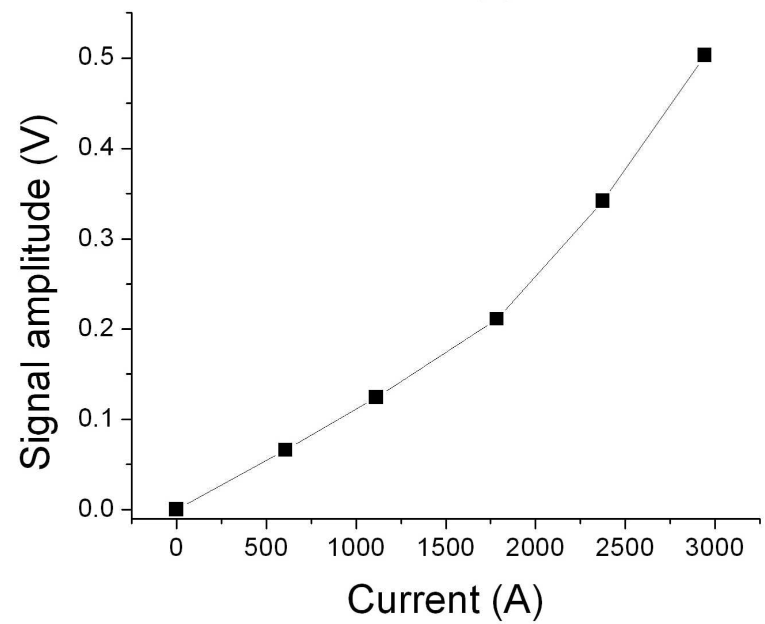


- Faraday mirror rotates polarization 90 degrees and provides initial minimum output state

- Faraday Rotation sensor signal amplitude increases with increasing current due to:
  - (1) Faraday rotation – dominates at lower currents
  - (2) Reduced power scattering – dominates at higher currents

- More linear overall response
- Reduced signal amplitude due to insertion loss from polarizer





Summary

- Presented dc and transient results on a novel non-polarizer-based optical current monitor which could enable lower-power sensor systems
- Analyzed power scattering, DOP and Faraday rotation effects as a function of external magnetic field
- Demonstrated a compact Faraday-rotation-based optical current monitor with a more linear response
- For both sensors, current transients with 150-ns rise times where detected up to peak currents of ~2500V/2900A – limited by CDU range

- Sensitivity in specific current ranges can be optimized by using external magnet bias and/or adjusting sensor distance to stripline and optical axis angle.
- Future work includes reducing the size of the overall sensor to enable better sensor embedding and improve linearity of sensor response

- Acknowledgment and thanks to Alex Robinson, Randy Williams, Richard Cernosek and the Embedded Evaluation program for technical and financial support

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