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Fiber-optic current sensors based on polarization coherence and power scattering in magneto-optical films

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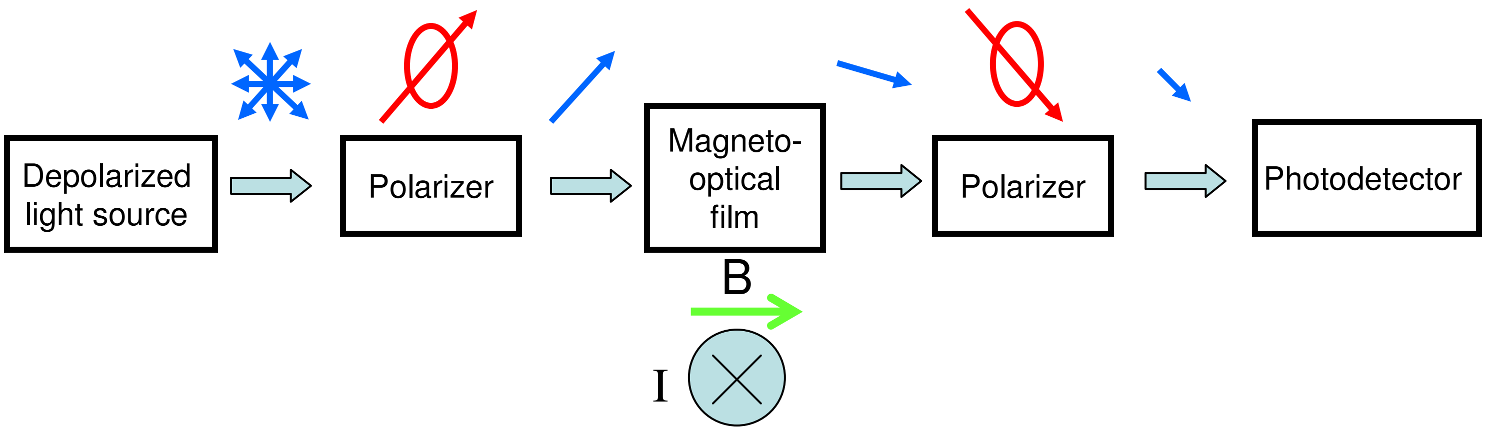
Motivation

- Monitoring of high-current signals is of interest for testing firesets

- 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

Magneto-optical materials

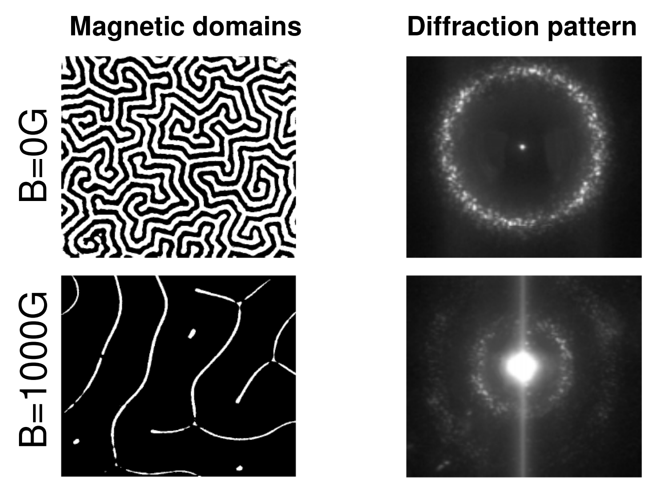


- Optical current monitors to date have predominantly used the non-reciprocal Faraday rotation effect in magneto-optical crystals to measure changes in current-induced magnetic field

- 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 also effects light propagation and diffraction via scattering with magnetic domains

(YbTbBi)IG film

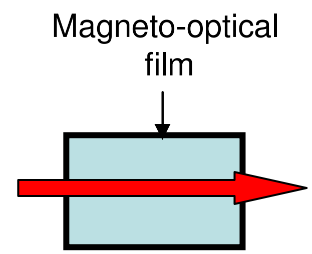


H. Sohlstrom, Ph.D. Thesis, RIT

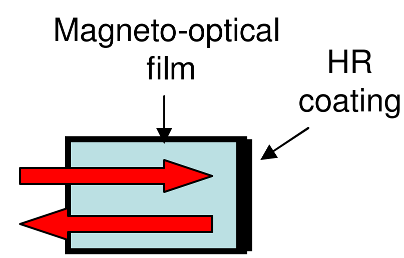
Approach

- 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 m 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

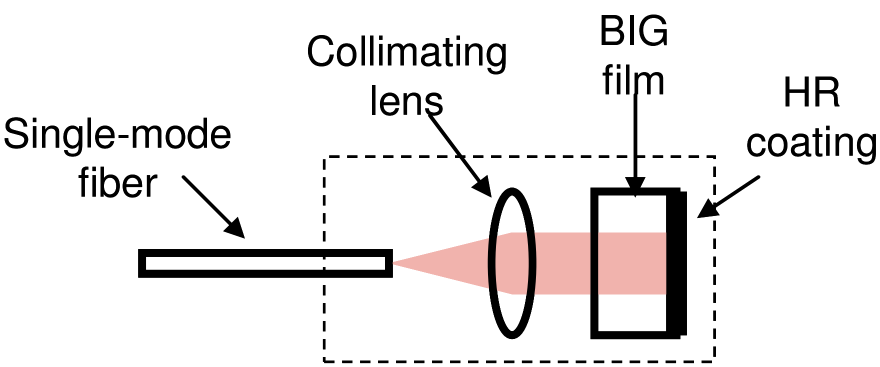


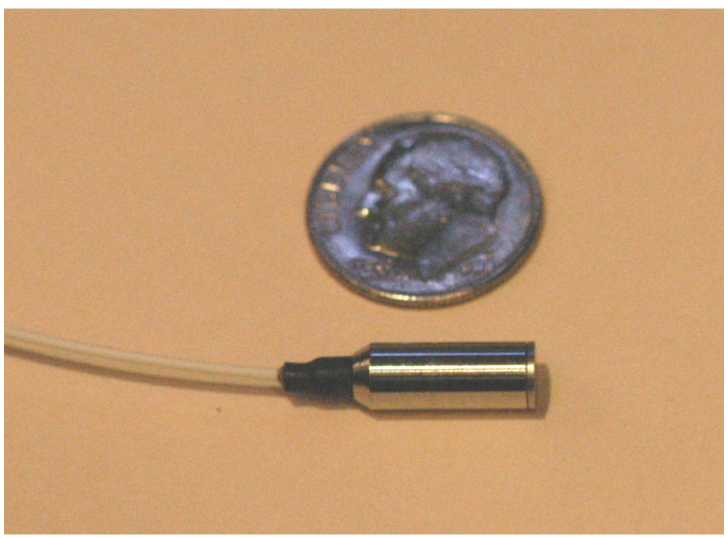
Transmission geometry



Reflection geometry

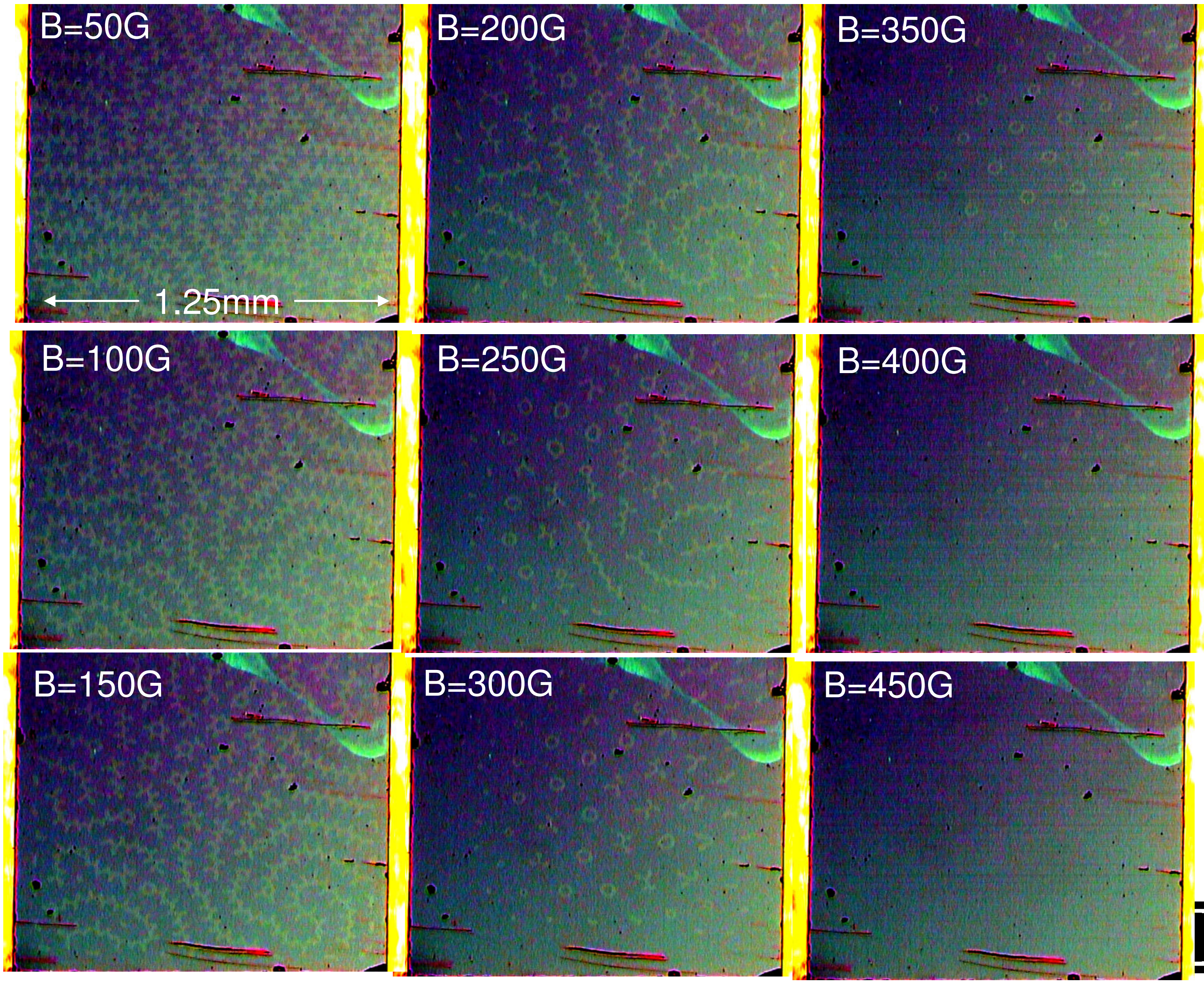
Packaged reflective optical monitor





- Custom packaged sensor was fabricated to enable more flexible testing compared to free space components
- Sensor consists of:
  - Aspheric lens for beam collimation
  - 0.5-mm-thick BIG film with a high-reflectivity coating on the backside of the film

Magnetic domains in BIG film with applied B



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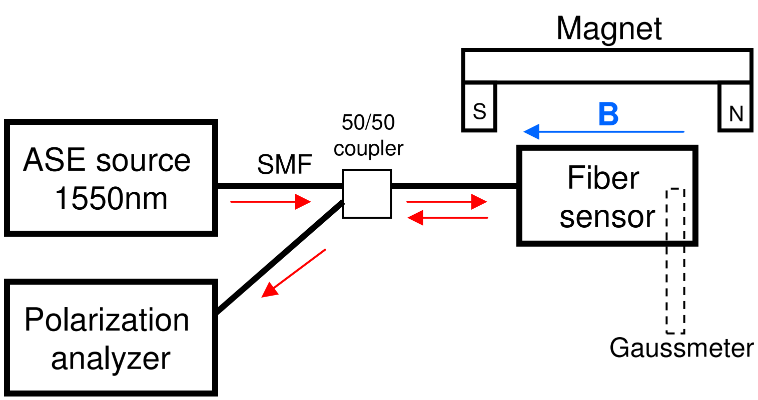
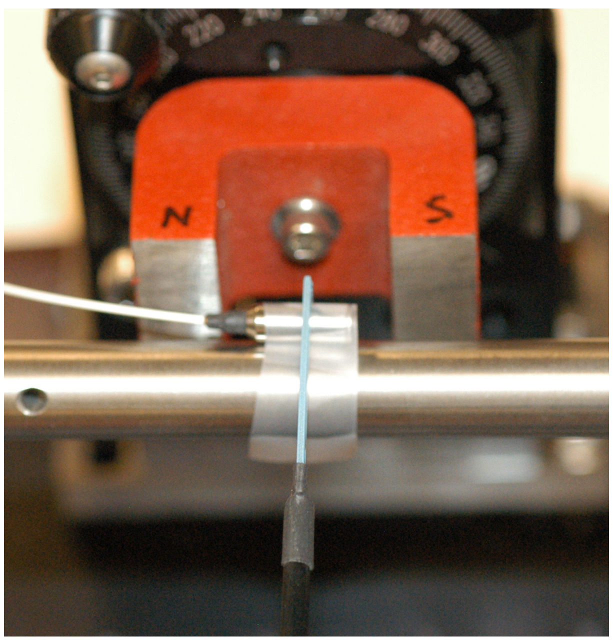
DC polarization analysis with magnetic field





- 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

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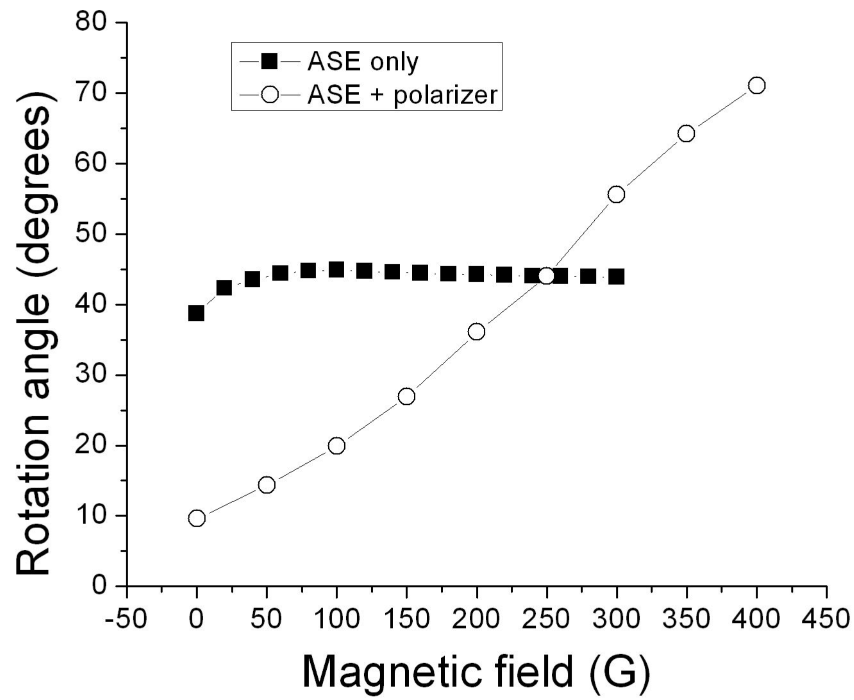
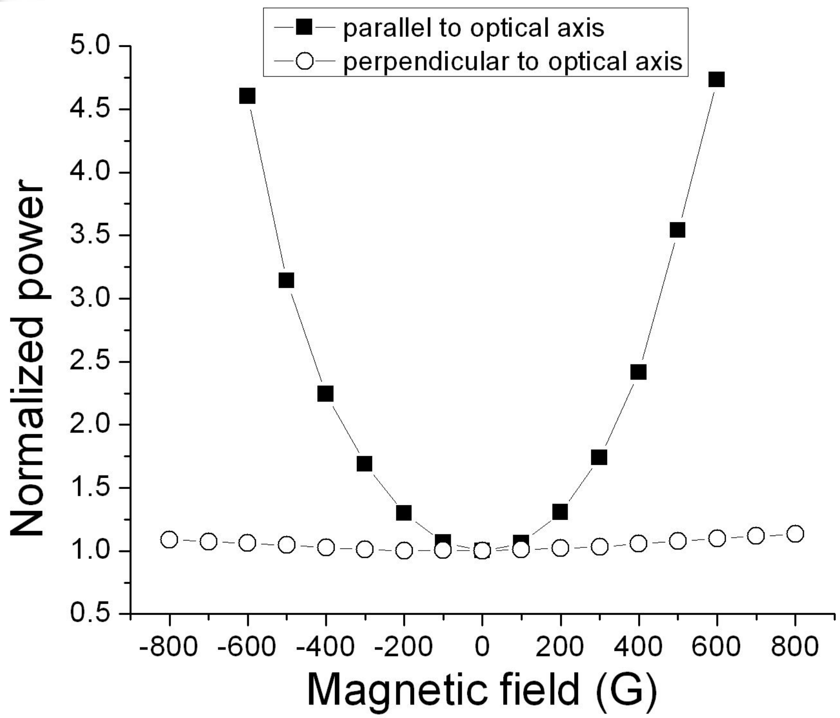
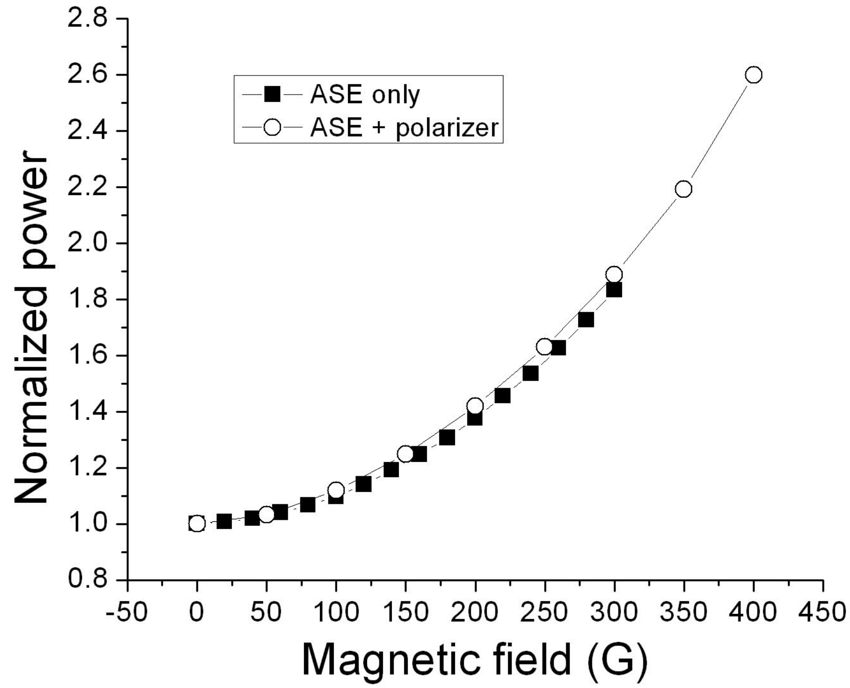
Faraday rotation

- 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 B^2 dependence
- Relatively independent of input power, polarization and DOP

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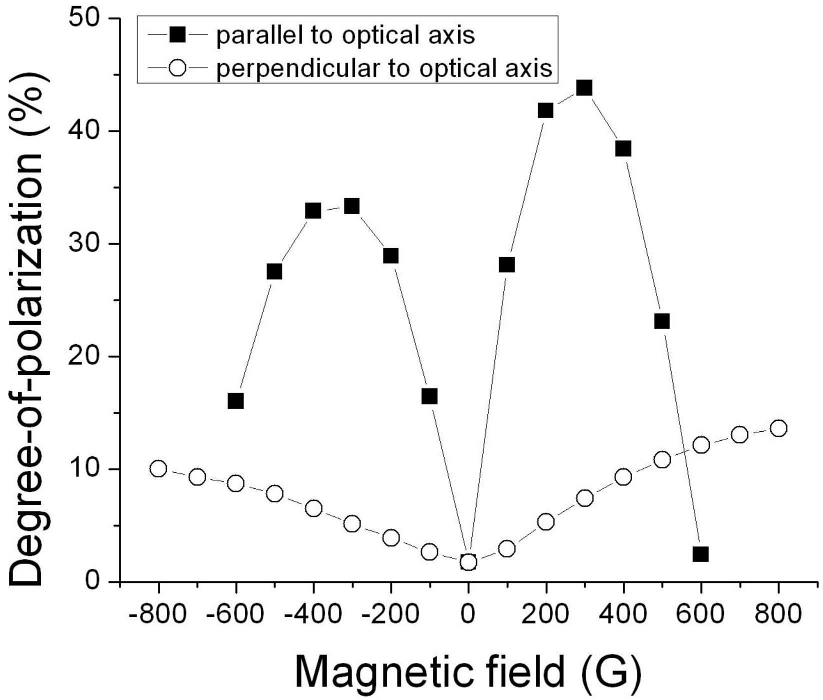
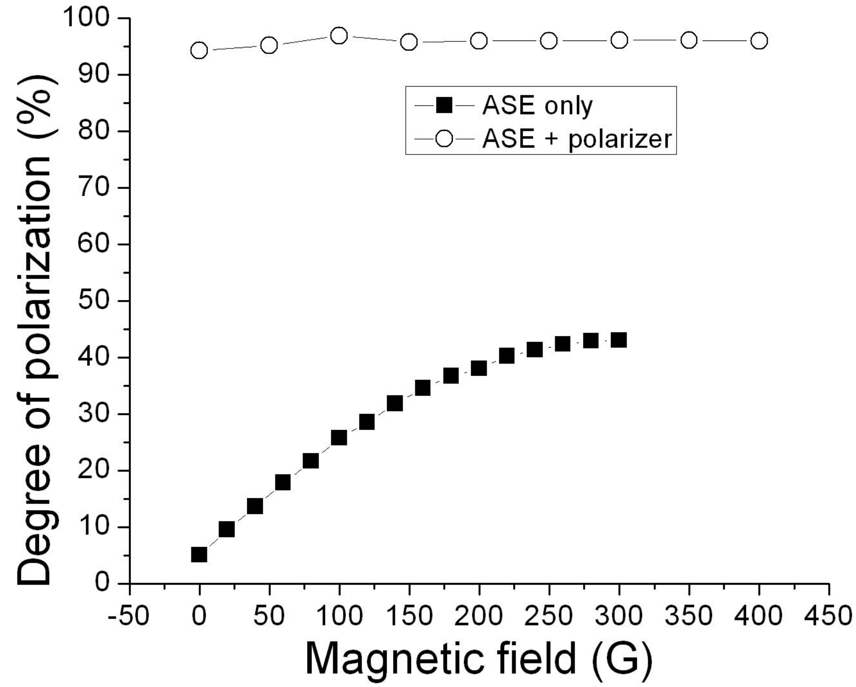
Degree of polarization

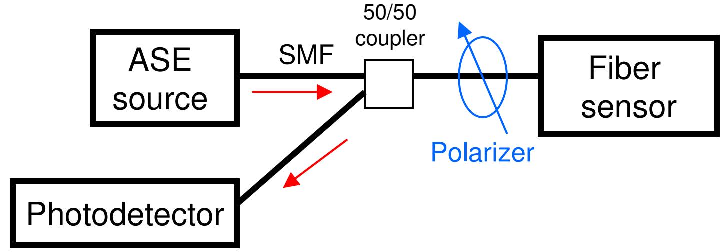




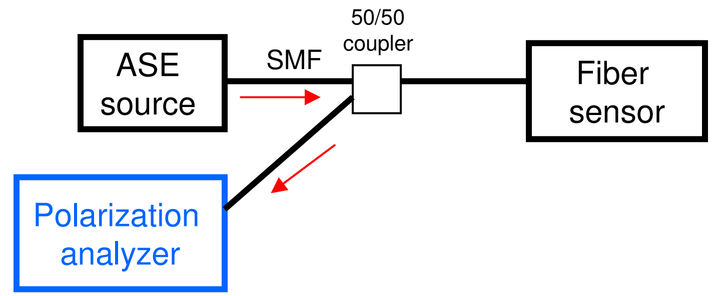
- Change in degree of polarization (DOP) shows periodic behavior with B. Increase as high as ~40% for magnetic field parallel to optical axis
- Increase in DOP also observed for perpendicular magnetic field
- Change in DOP not observed for highly polarized light input case

Sensor system considerations

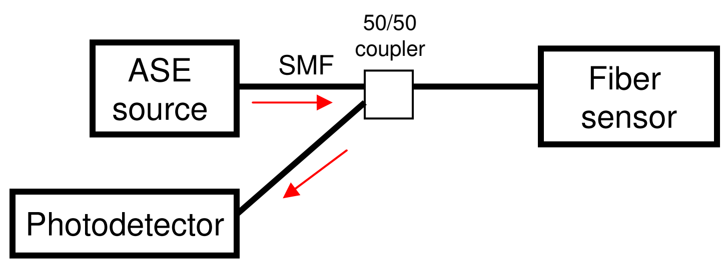
- Faraday rotation mode (standard)
  - Linear response
  - ~10-20dB insertion loss from polarizers necessitates higher source power



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



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



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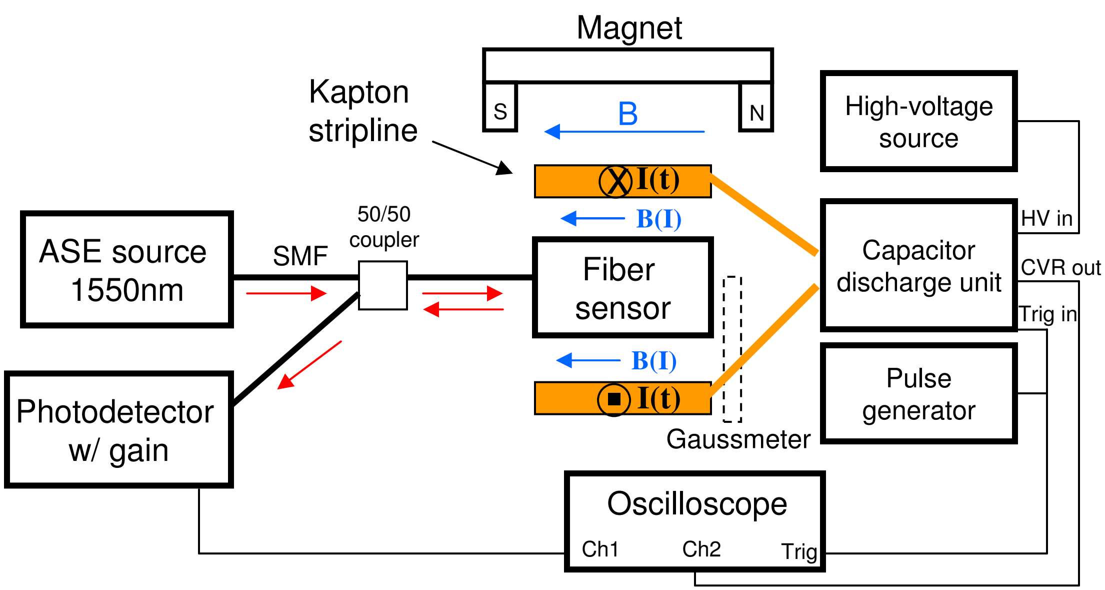
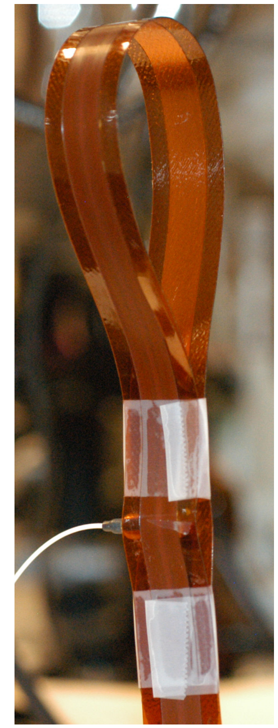
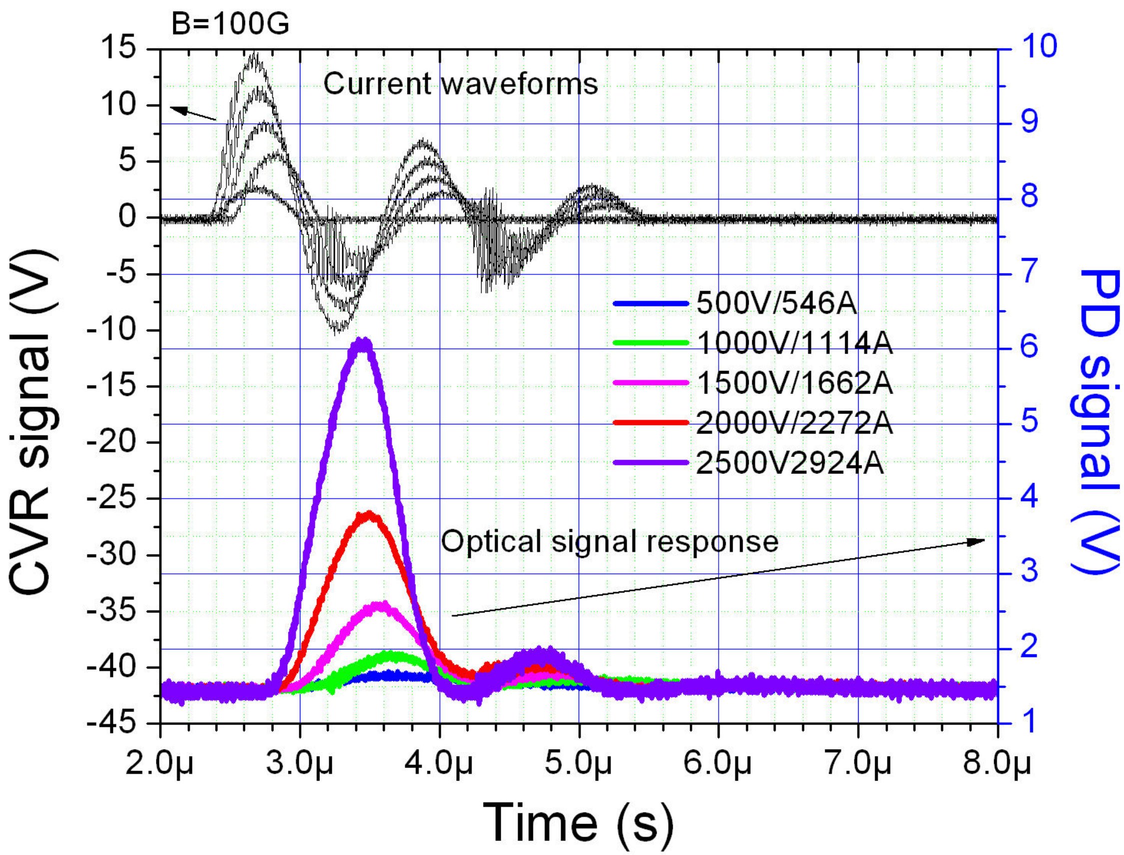
Transient current pulse testing





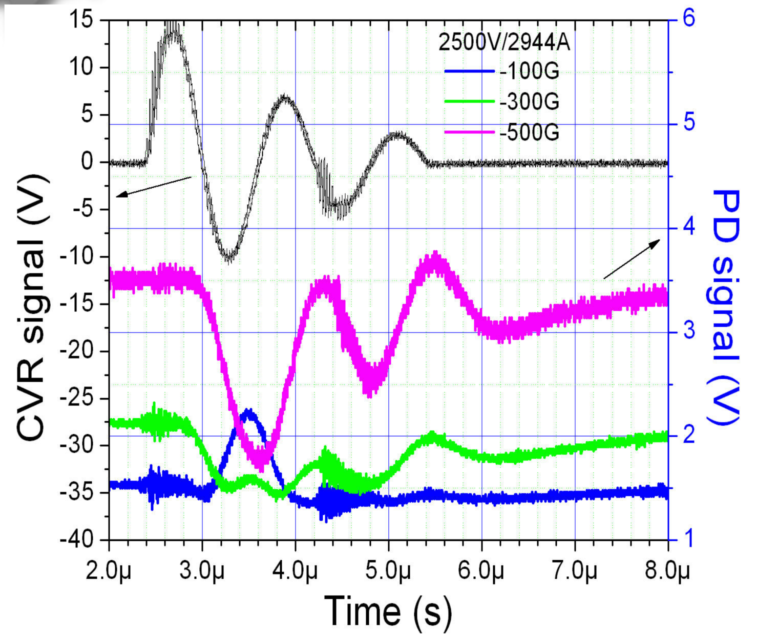
- Capacitor discharge unit (CDU) produced current pulses up from 500A to ~3kA peak current with 150-ns rise times over Kapton stripline with 10-mm-wide conductor
- Measure corresponding optical response from fiber sensor sandwiched between Kapton lines
- Also evaluate optical response as a function of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

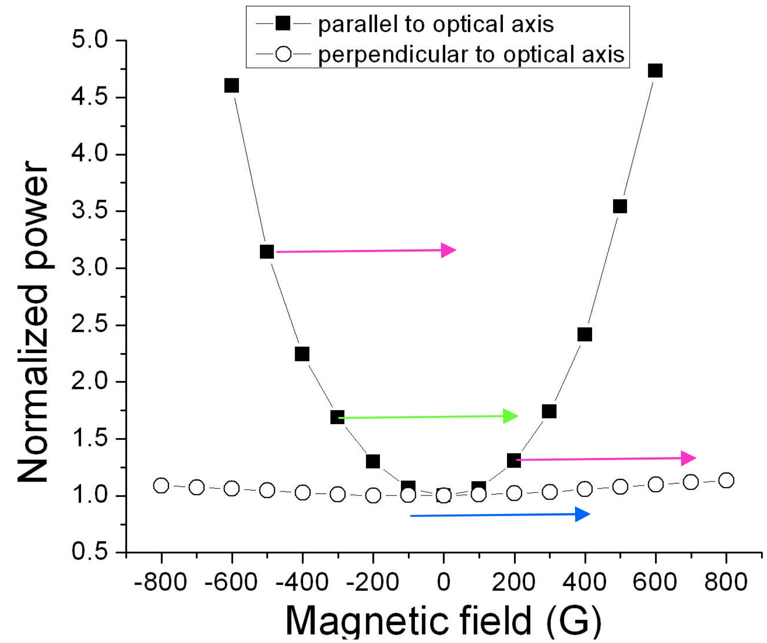
Transient sensor response

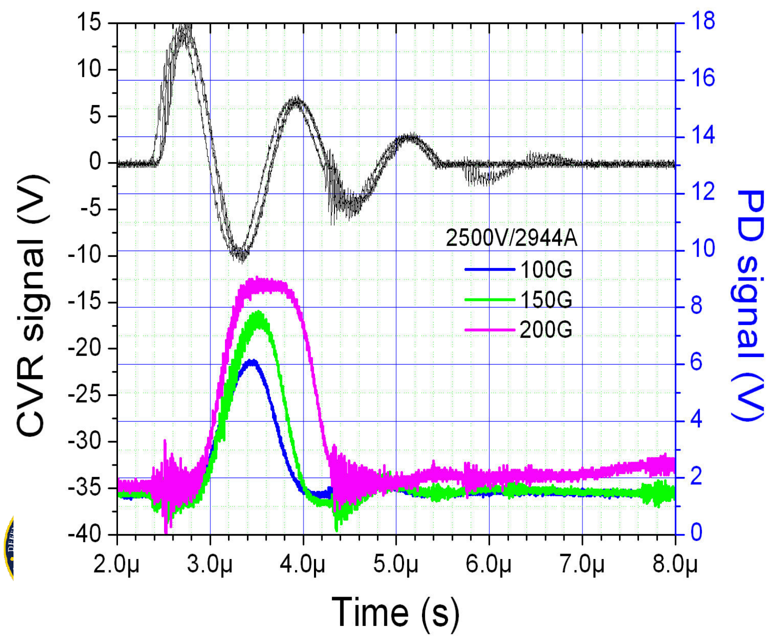


- Optical response observed up to ~2500V/3000A (limit of CDU)
- 500-ns delay between current waveform and optical response
- Slightly broader optical response, negative current swings and secondary transients not well resolved
- Measure peak signal amplitude of optical response as a function of peak 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 that 2500V/2944A corresponds to B=~450G for this sensor and position
- For positive B, 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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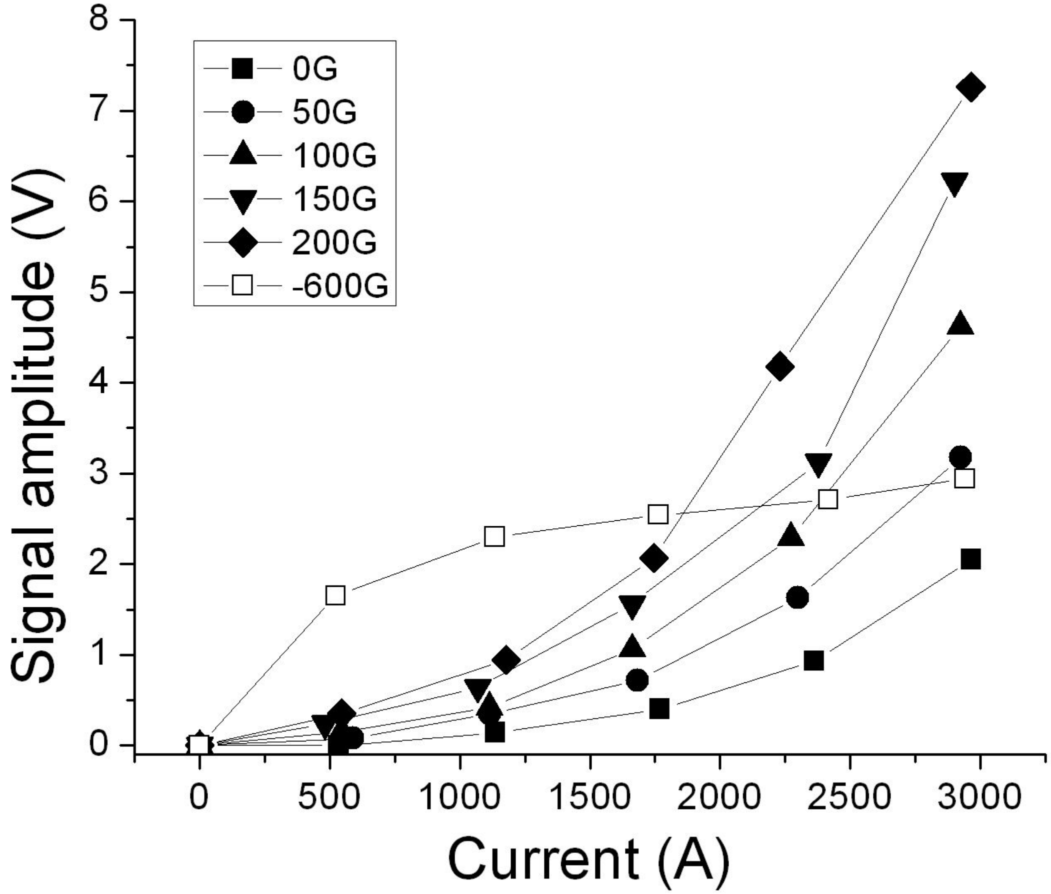
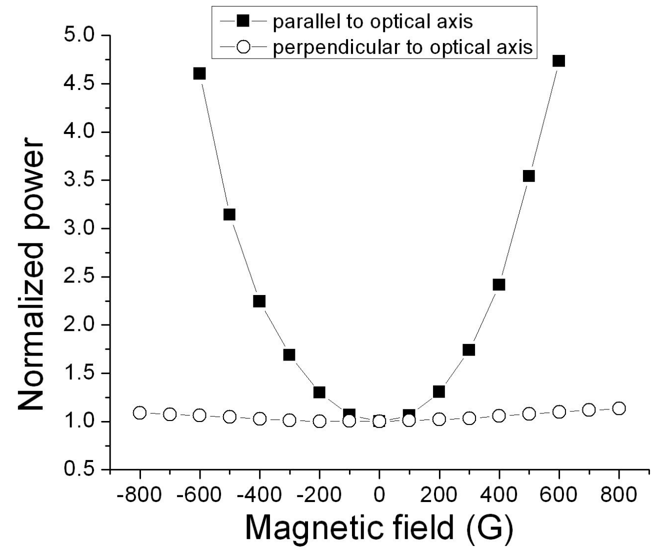
Transient sensor response summary





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

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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
- 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 sensor embedding and improve linearity of sensor response