Electro-Optic Sensors for RF Electric Fields: a Diagnostic Tool for Microwave Circuits and Antennas

Electro-Optic Sensors for RF Electric Fields: a Diagnostic Tool for Microwave Circuits and Antennas

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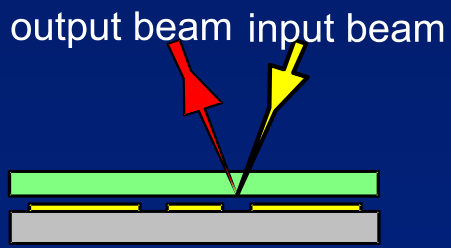
Outline

- Motivation & Background
- Fundamental Concepts of Electro-Optic Probing
- System Configuration & Attributes
- Diagnostic Measurement Examples
- Thermal & Magnetic-Field Imaging

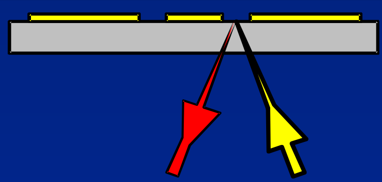
Motivation

- Near-field measurements – radiating structures
  - High spatial resolution at h << λ
  - Observation of nonradiating waves
  - Near-to-far-field transformation
- Near-field measurements – guided-wave structures
  - Internal-node characterization
- Near-field diagnostics - fault isolation
  - Detect malfunctioning components
  - Determine relative phase of sources
- Design/performance verification
- Model Validation

Electro-Optic Sampling Probe Embodiments

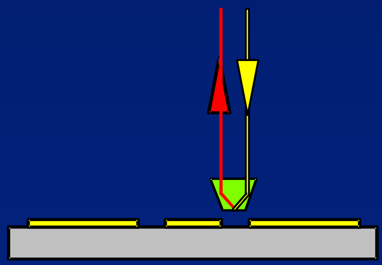


integrated type



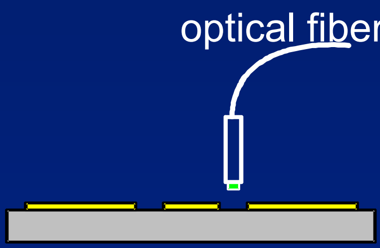
substrate probing

1st Generation



external (free-space)
EO probing

2nd Generation



fiber-based EO probing

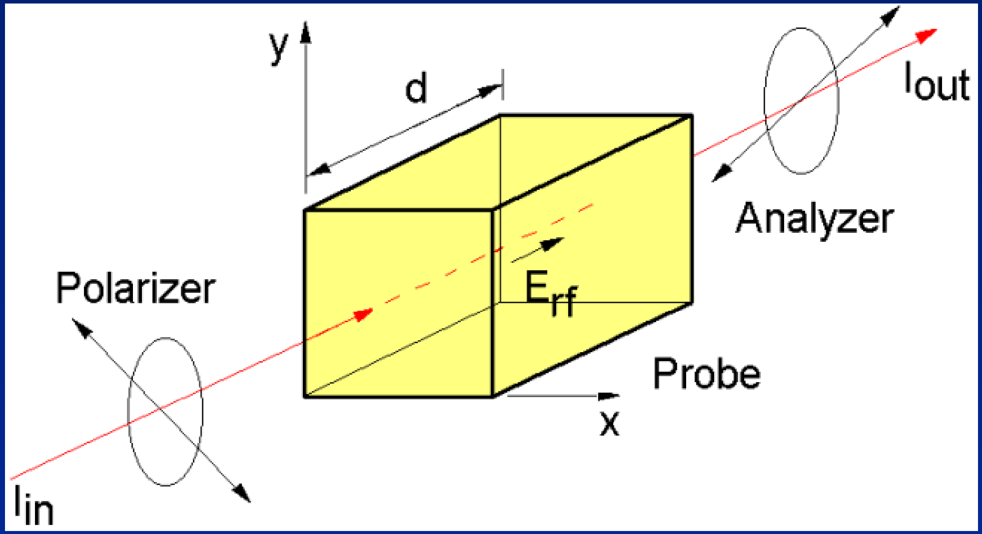
3rd Generation

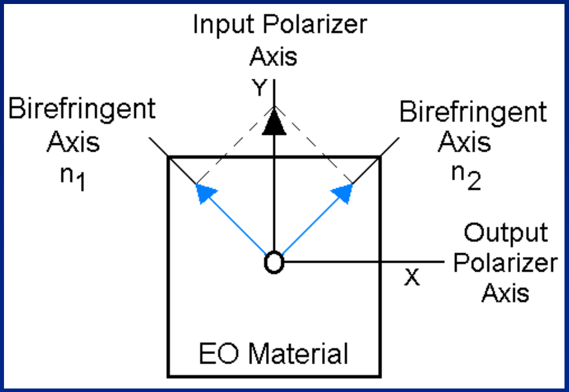
Additional field-mapping concept & applications references:

- U. Colorado – Boulder
- U. Duisberg
- U. Aachen
- NTT (x2)
- NPL
- U. Maryland
- Brunel Univ.
- U. Tokyo

Principle – Electro-optic Effect

- RF electric-field measurements based on electro-optic (Pockels) effect.





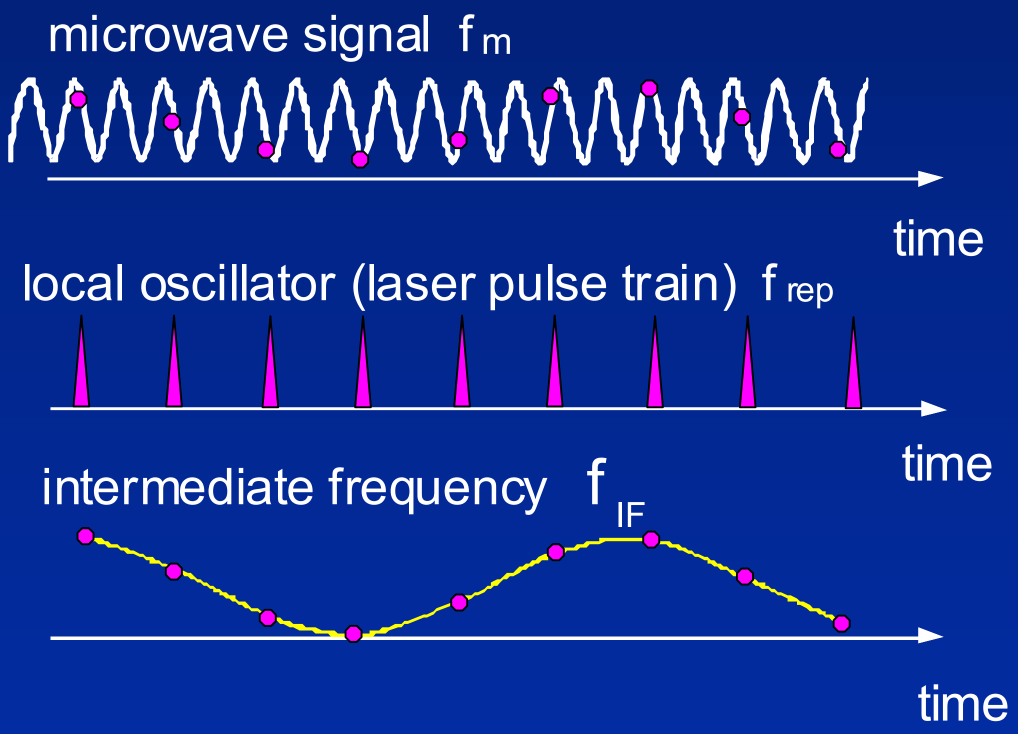
- External polarizers are cross-polarized.

- Change in polarization state due to electric field induced *linear* birefringence.

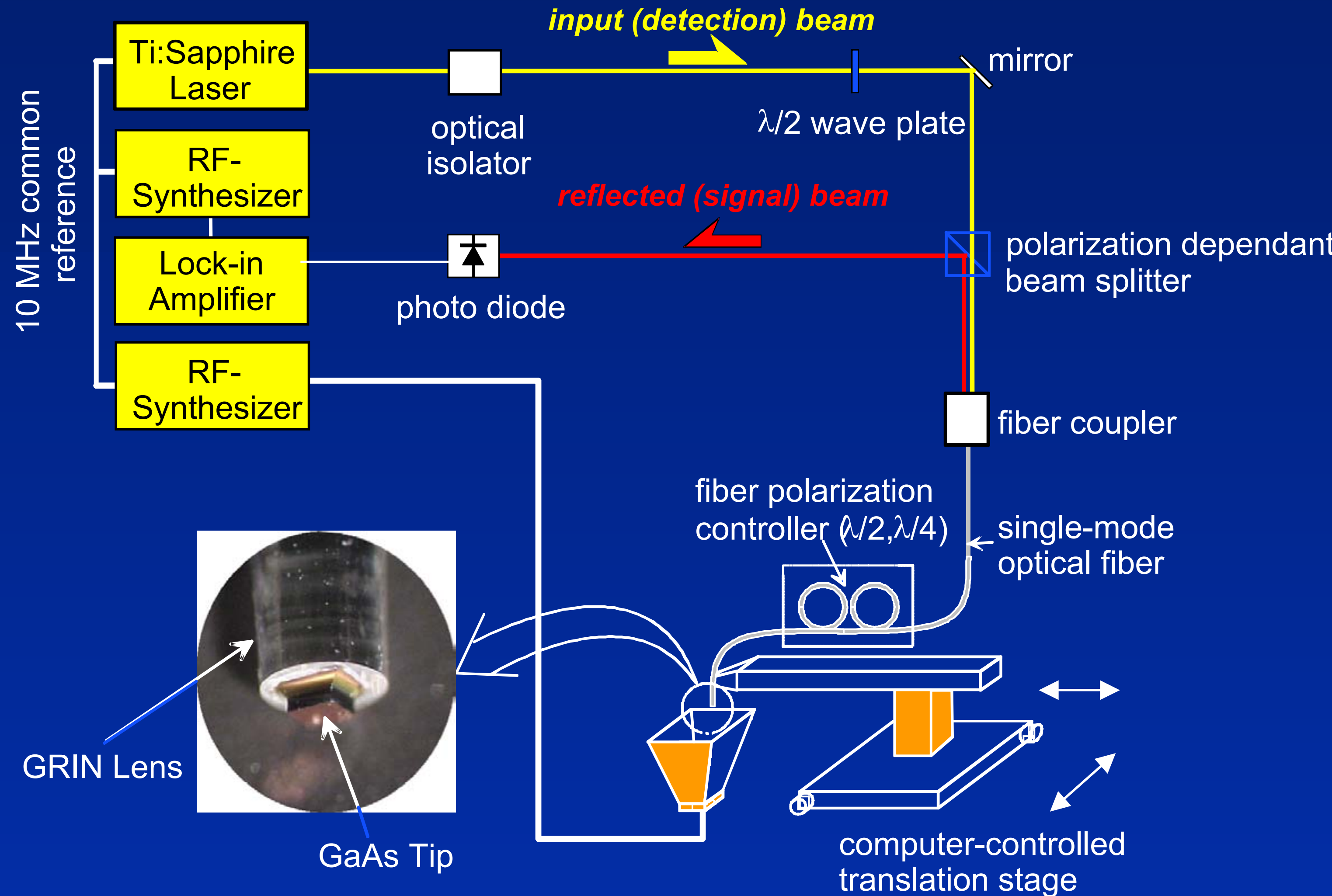
Electro-Optic Equivalent-Time Sampling for High-Bandwidth Measurements

Principle:
Harmonic Mixing

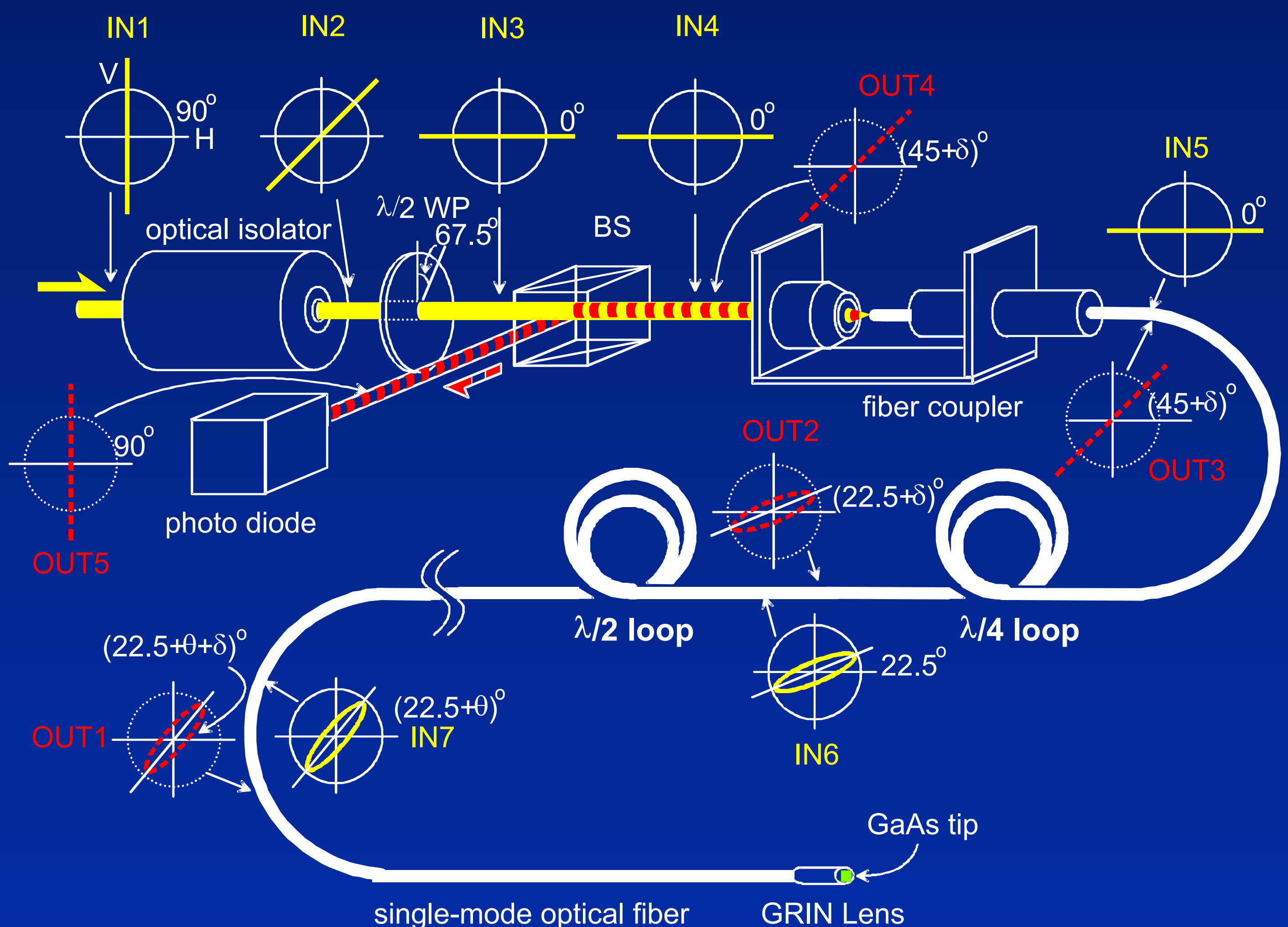
$$f_{IF} = f_m - n \cdot f_{rep}$$



Fiber-Based EO Field-Mapping System

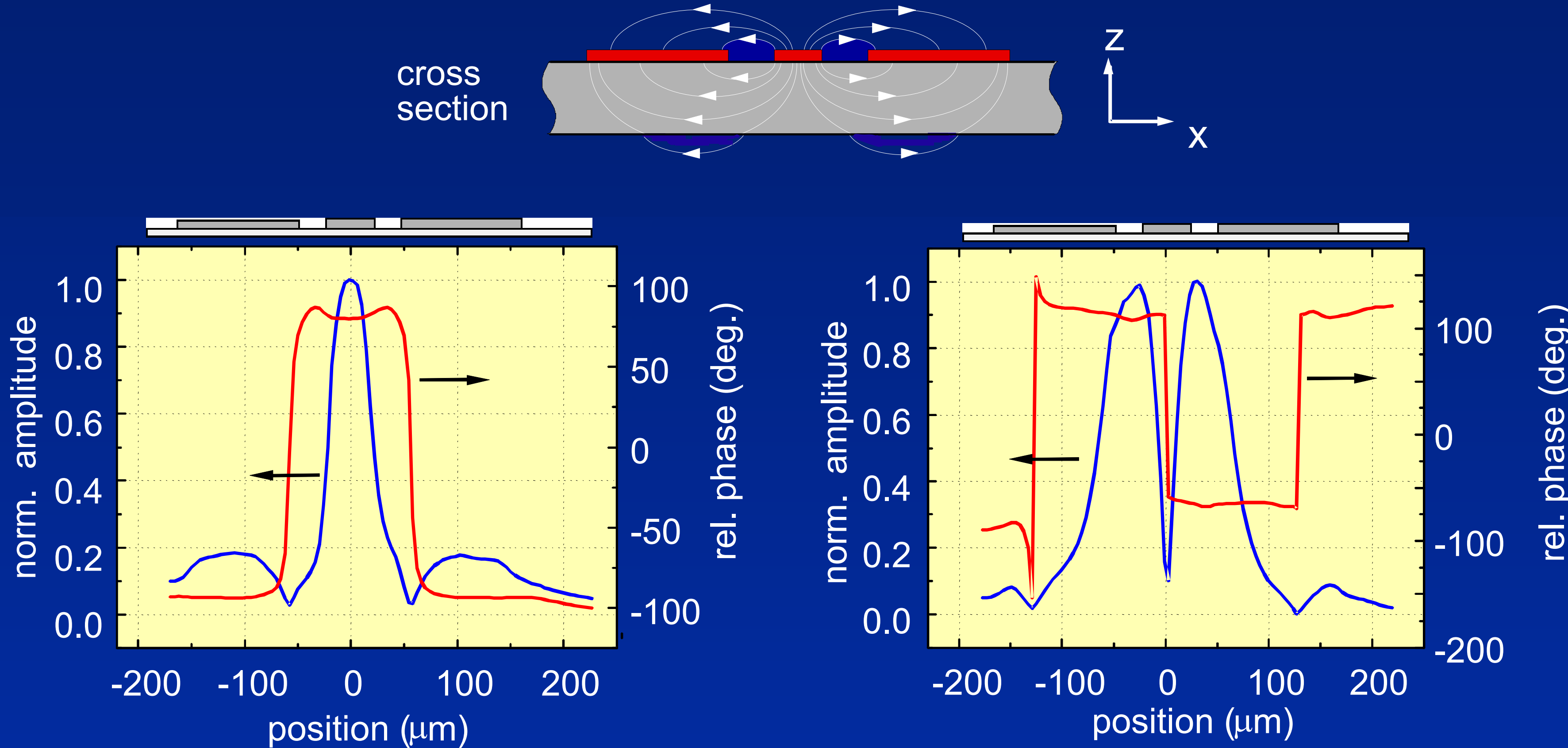


Polarization Control in an Electro-Optic Probing System



1-D Electro-Optic Field Mapping

Coplanar Waveguide Transmission Line cross Section



Normal field component

Tangential field component

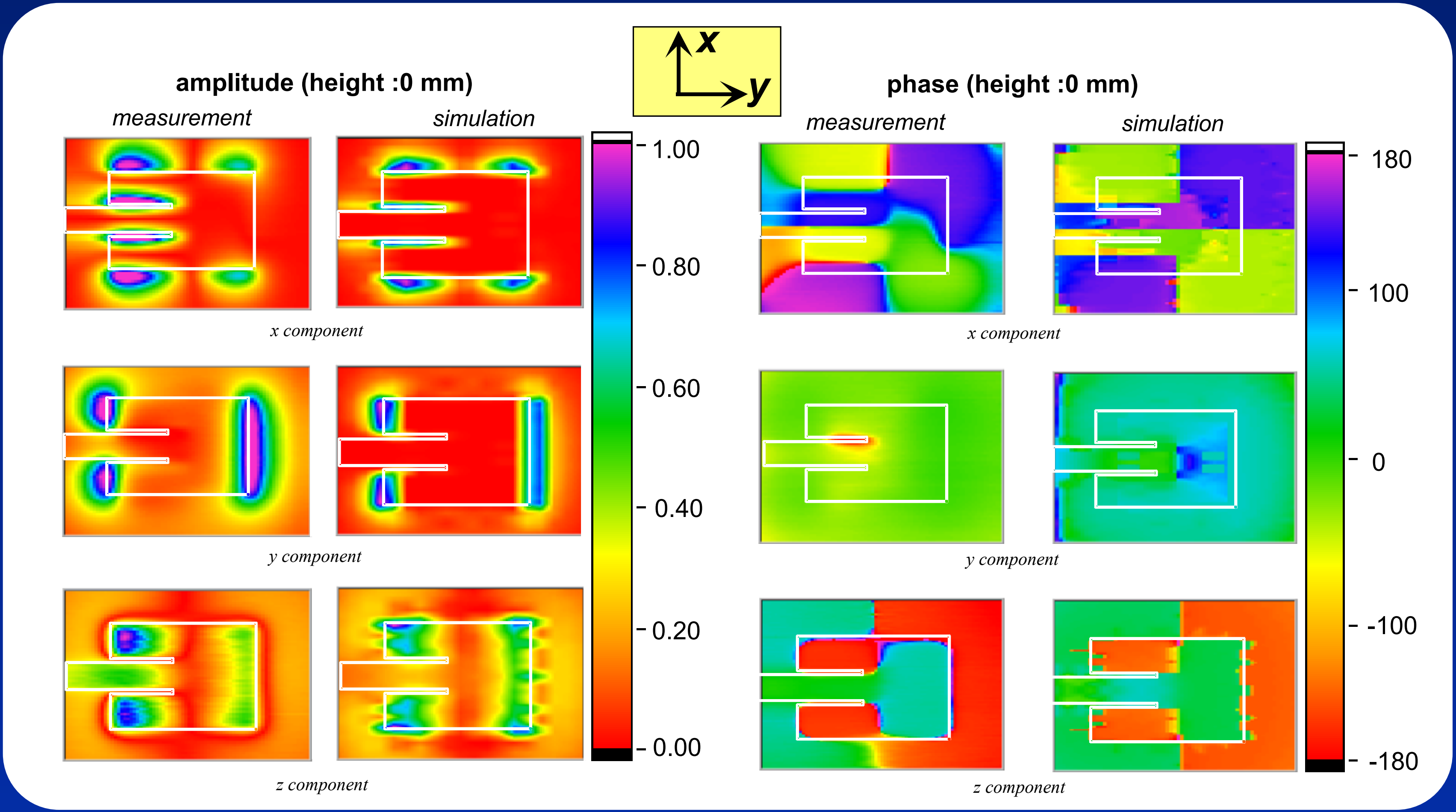
Electro-Optic Electric-Field-Sensing Capabilities

- Extract both amplitude and phase of electric fields
- Isolate X, Y, and Z vectorial components
  - (110) GaAs probe tip for tangential fields
  - (100) GaAs probe tip for normal field
- Near-field measurement (range < 100 μm)
- Low invasiveness
  - probe much smaller than wavelength
  - no metal near field to be measured
  - finite difference simulations indicate small changes in Z_c for typical probe heights
- High positioning flexibility with fiber coupling

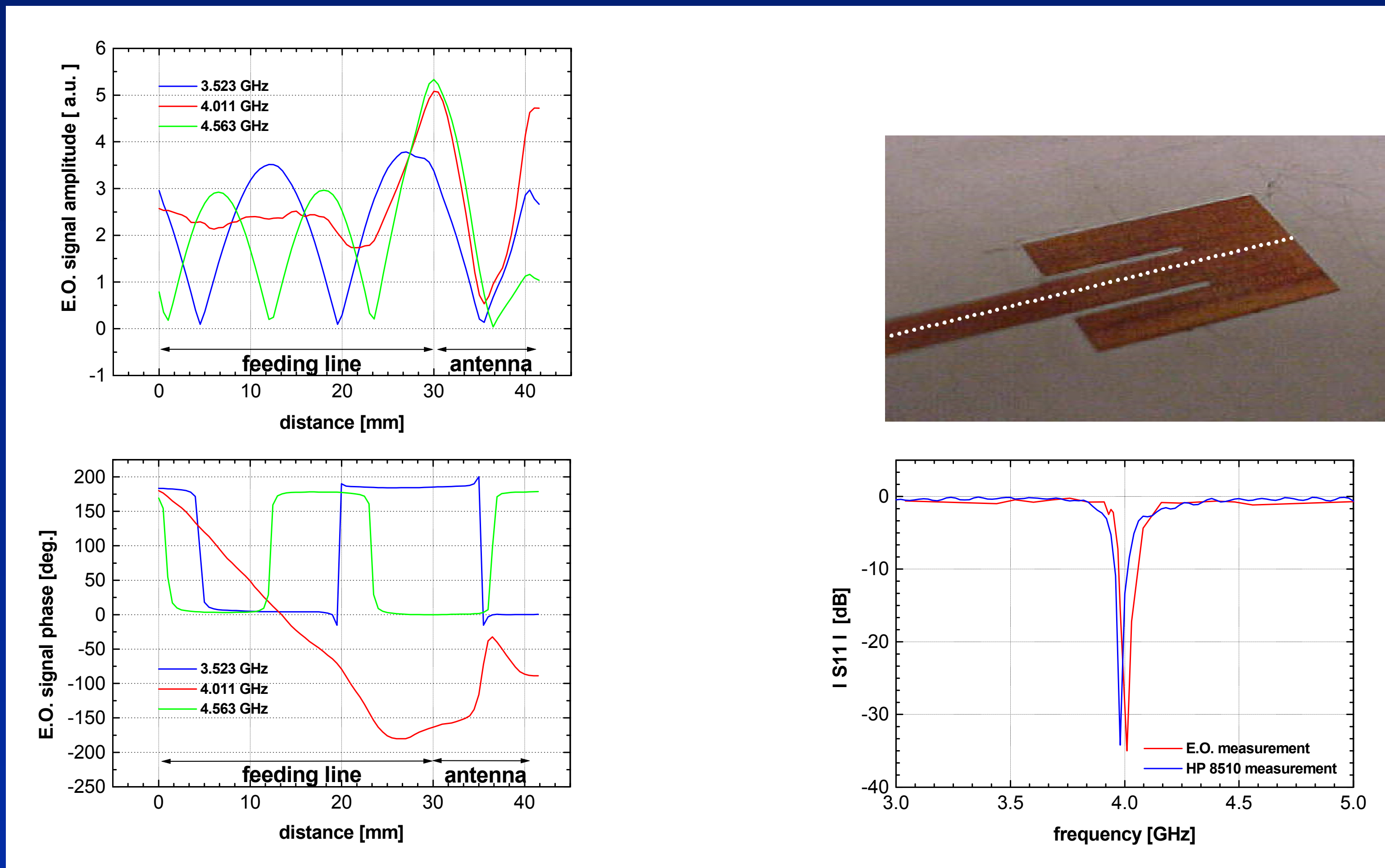
Electro-Optic Electric-Field Sensing: System Performance

- Bandwidth: >100 GHz
- Spatial Resolution: < 8 μm
- Phase stability: +/- 3°/hour
- Cross Polarization Suppression: > 30 dB
- Time for Measurement: 15-60 min.
- Area of measurement: micrometers to meters
- Sensitivity: < 1 V/m/(Hz)$^{1/2}$

Electro-Optic Field Mapping of a Microstrip Patch
- Measurement vs. FEM Simulation

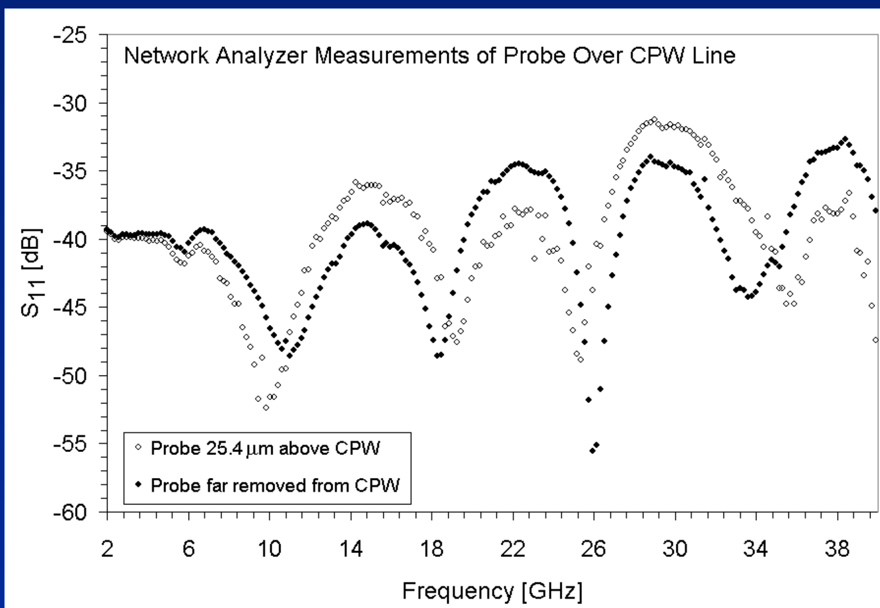


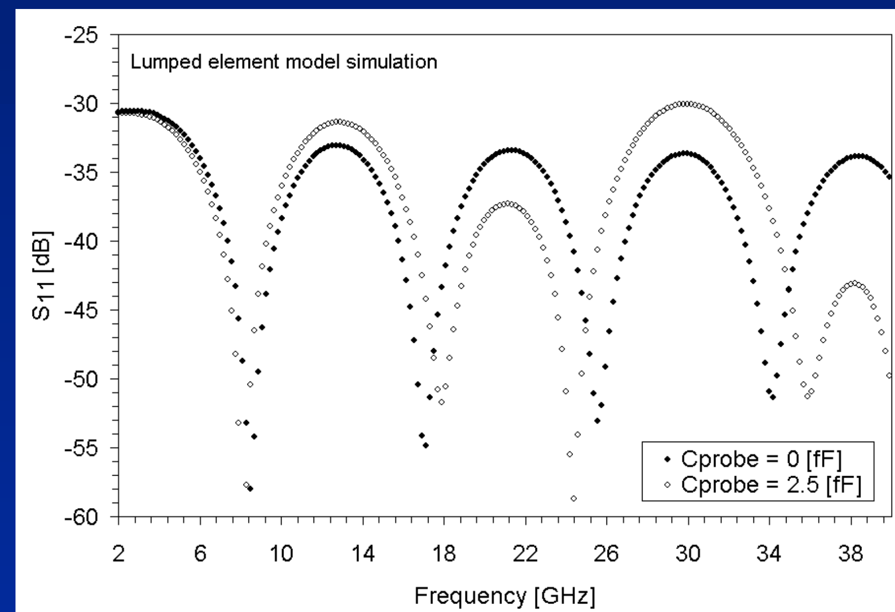
Electro-Optic Electric-Field Sensing:
S_{11} Measurement on Microstrip Patch Antenna



Field-Sensing-Probe Invasiveness

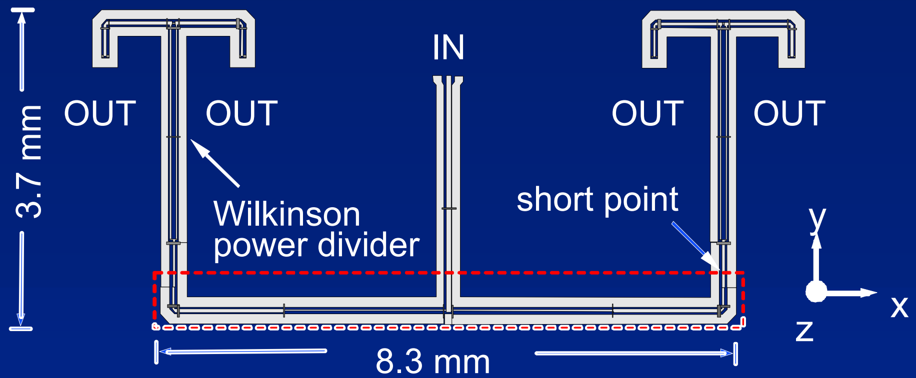
- Return loss from CPW measured and calculated with and without EO probe in position.





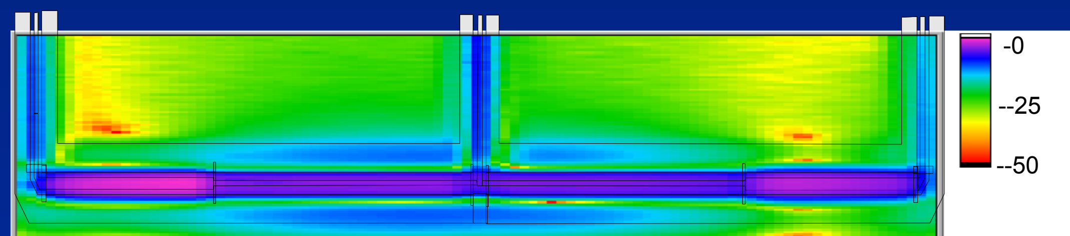
- Frequency domain measurements (2 - 40 GHz): |S11| < -30 dB with and without probe

Electric Field Sensing in a 1 X 4 Power Distribution Network: Operation and Fault Isolation

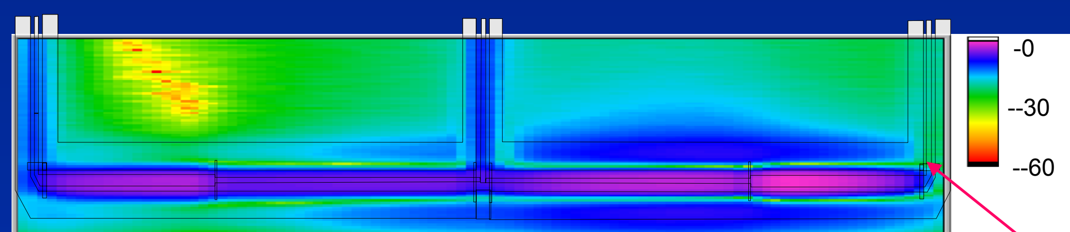


z-component, frequency: 15 GHz

matched circuit, amplitude (dB)



partially shorted circuit, amplitude (dB)

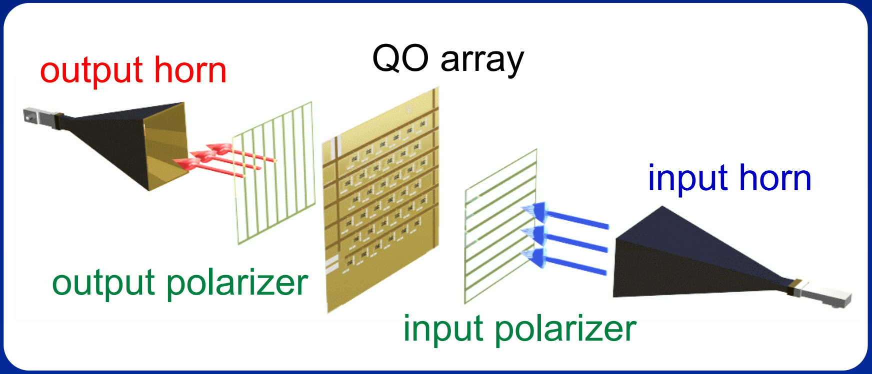


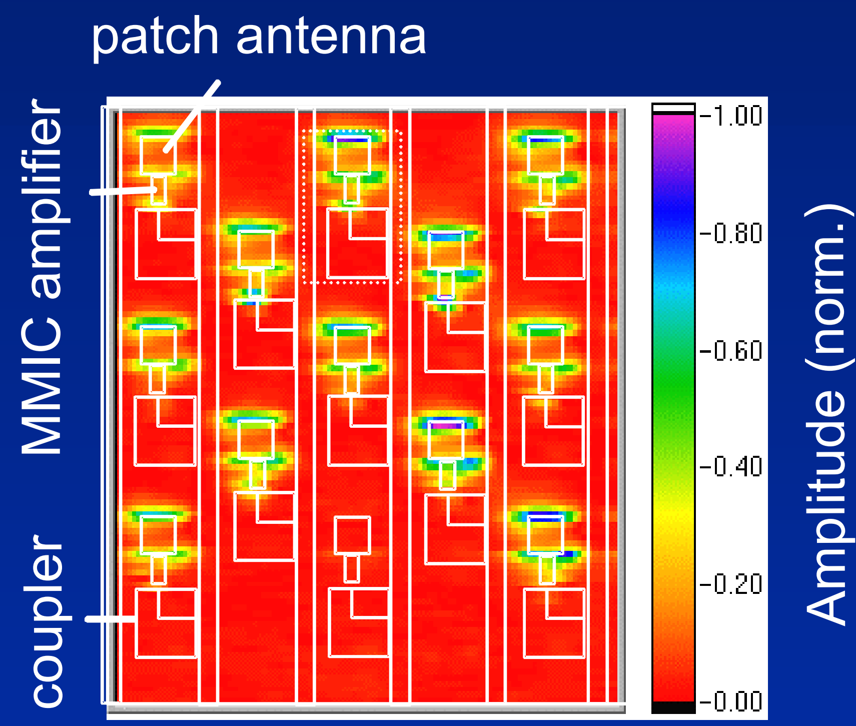
shorted air-bridge fault

Field Sensing in an Antenna Array

Diagnosis of Malfunction in a Ka-Band Quasi-Optical Amplifier Patch Array

Basic operating principle

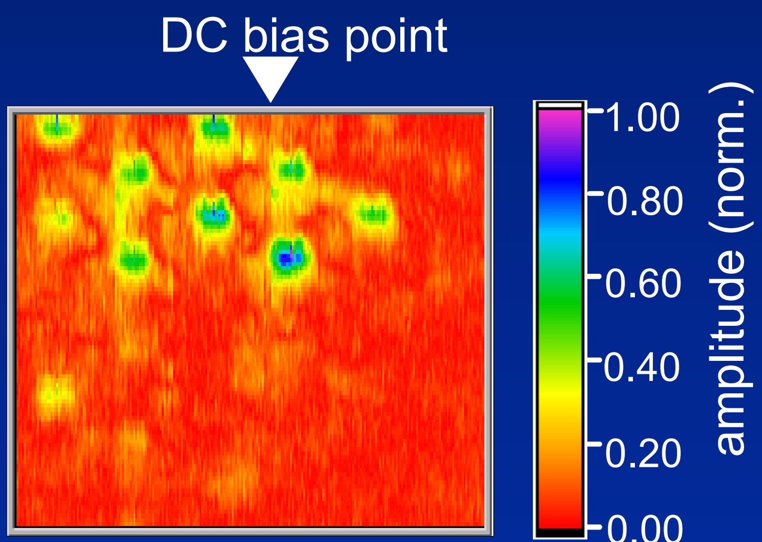


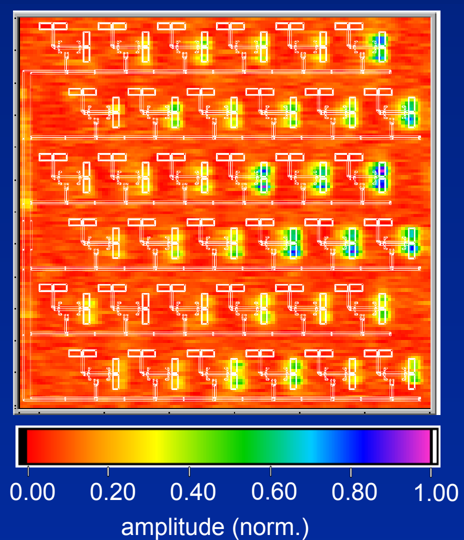


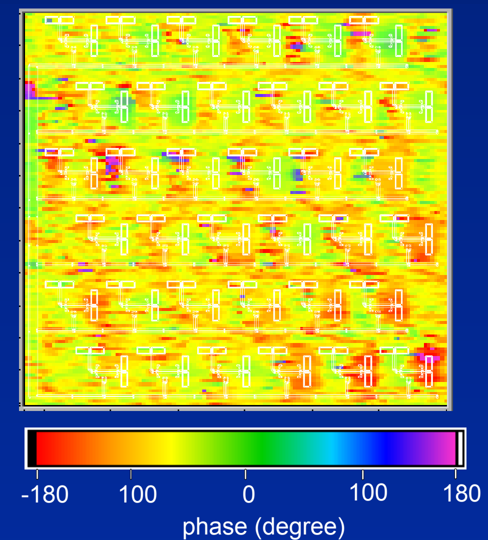
Array provided by Lockheed-Martin

Field Sensing in an Antenna Array

Ka-Band Quasi-Optical Amplifier Slot Array: Observation of parasitic coupling

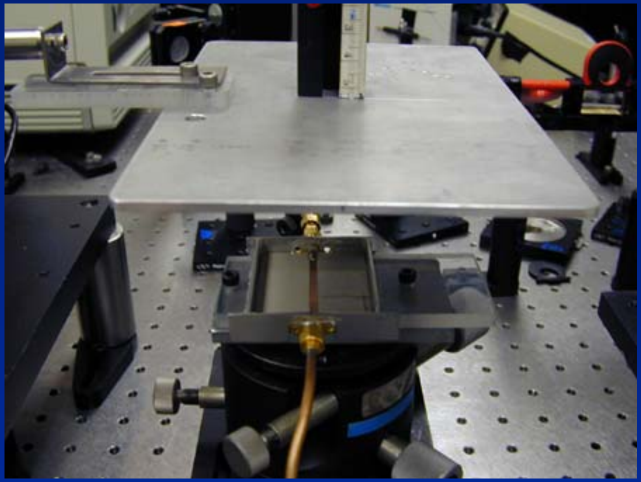


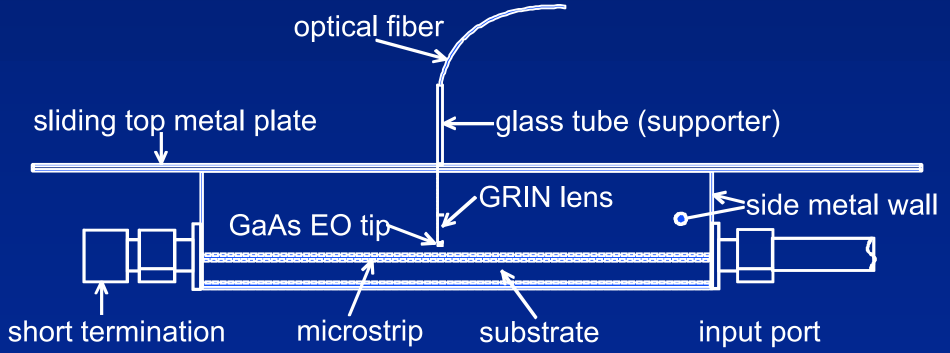




Array provided by Zoya Popovic
Univ. of Colorado - Boulder

Field Sensing Inside Microwave Packages
Shielded Microstrip at f = 8 GHz



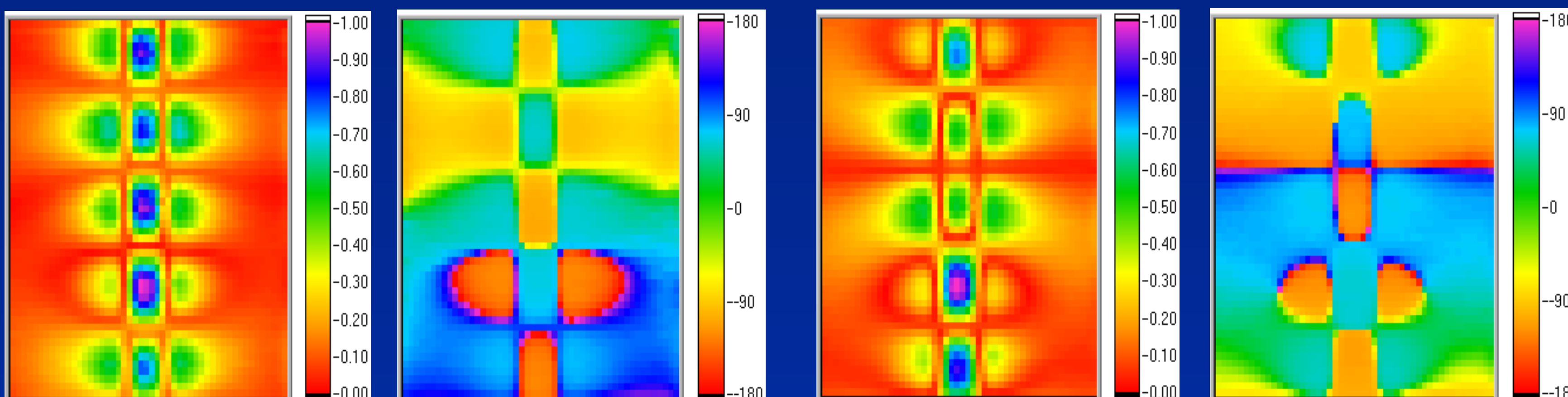


Shielded Microstrip (open side view)

Field Sensing Inside Microwave Packages: Shielded Microstrip Measurements

⦿**E** h = 1 mm

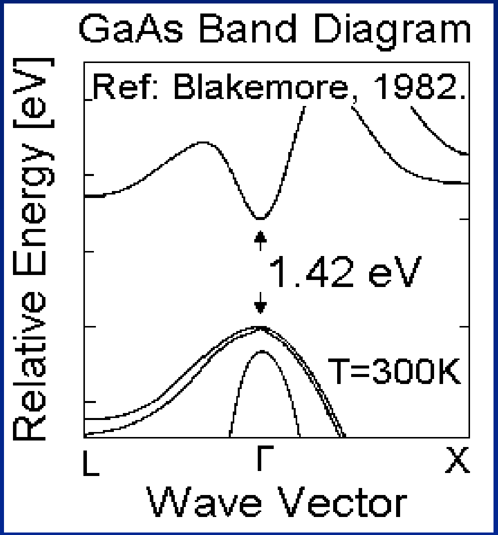
exposed microstrip *shielded microstrip*

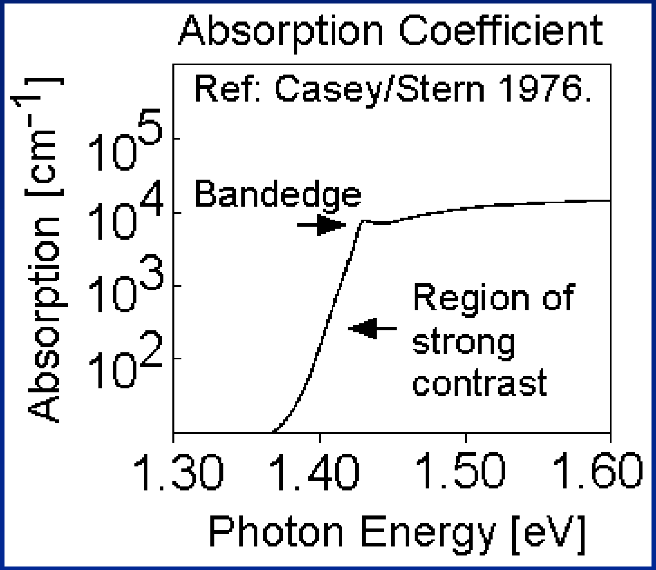


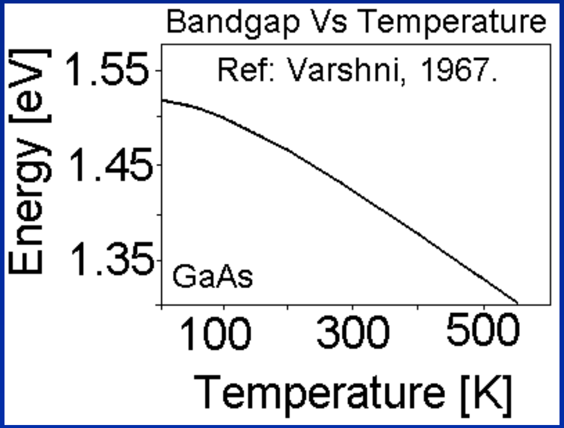
amplitude [norm.] phase [degree] amplitude [norm.] phase [degree]

Thermal Calibration, Sensing, and Imaging

- Temperature measurements based on optical absorption due to the temperature dependence of the band-edge in GaAs.





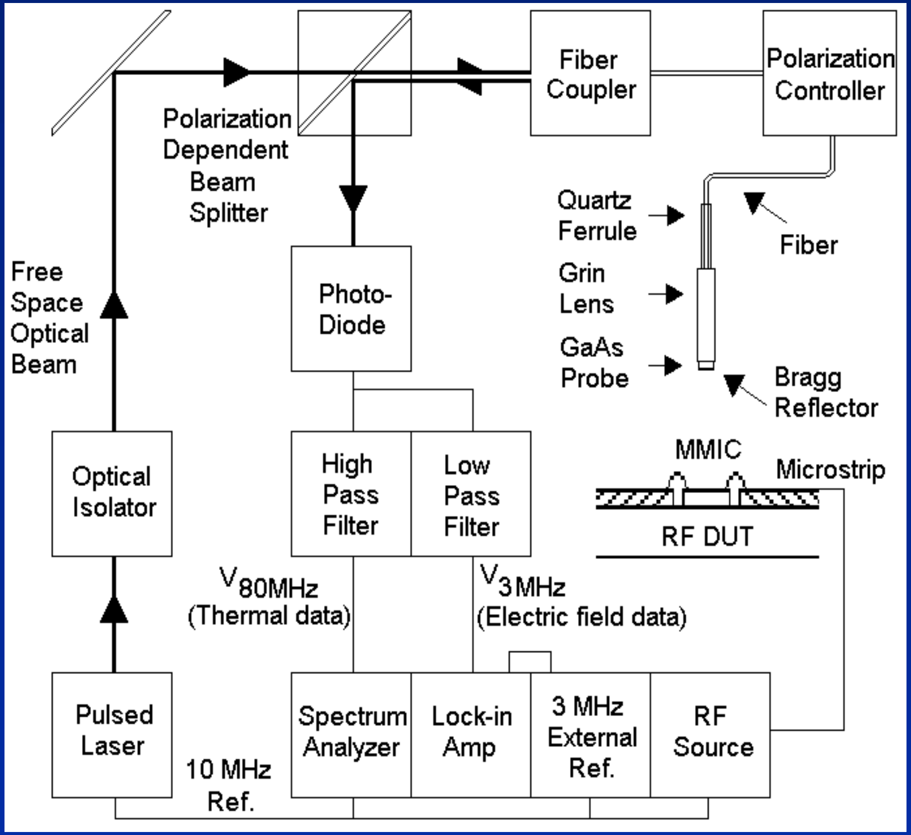


- Relationship between optical power (P) and temperature (T)

$$\frac{1}{P} \propto 1 + \kappa T$$

System Implementation for Simultaneous Electric Field and Temperature Sensing

• E-fields and thermal distributions can be measured at the same time with a single probe.



*Absorption → Temperature & E-field

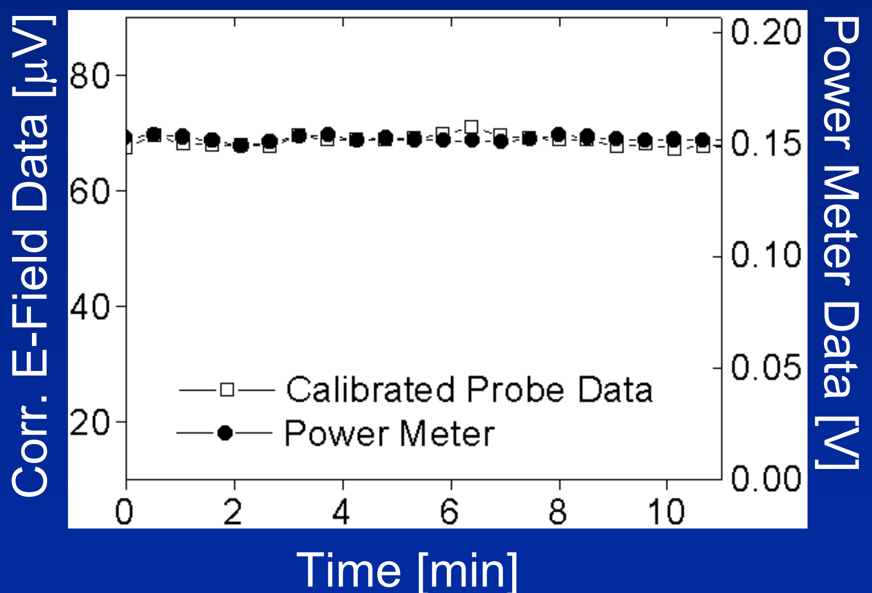
*Polarization-state → E-Field

Electro/Thermal Measurements on a Quasi-Optical Amplifier via Optical Sensor

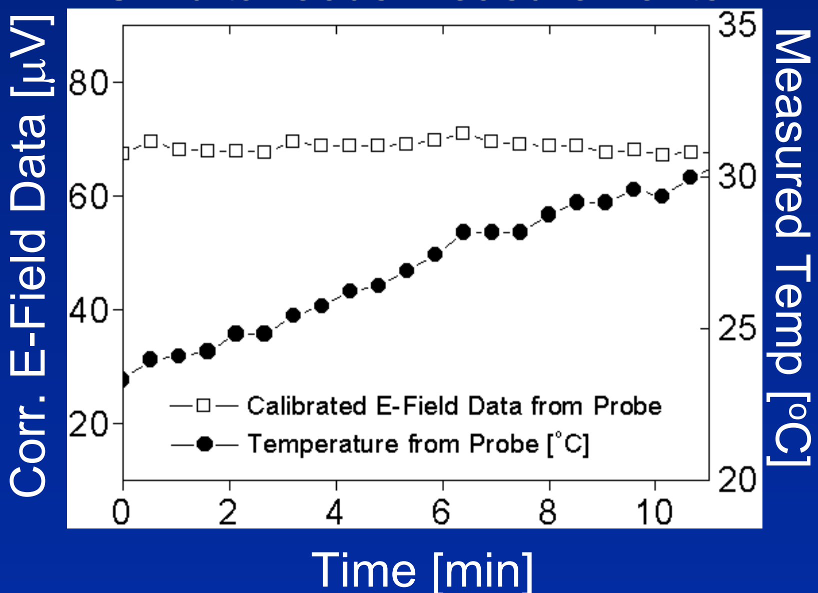
- Corrupted electric-field data corrected via:

$$V'_{3MHZ} = \left(\frac{dV_{3MHz}}{dV_{80MHz}}\right)\Delta V_{80MHz} + V_{3MHz}$$

Temperature Corrected Data



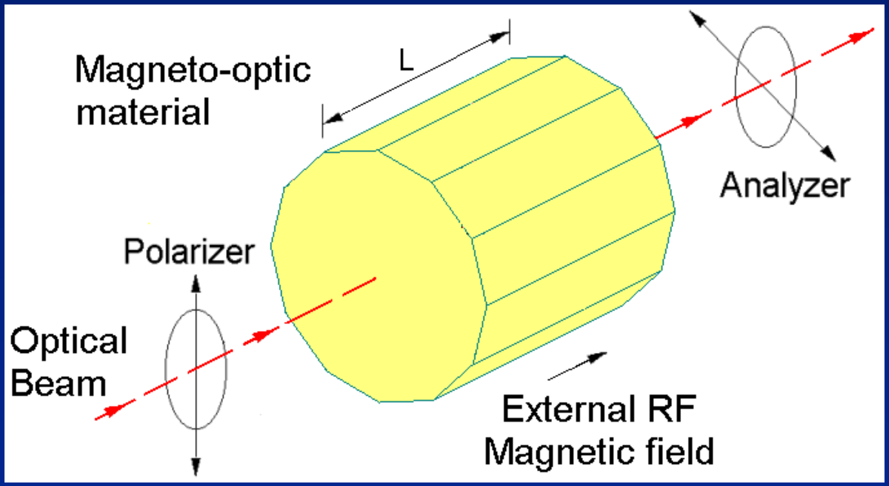
Simultaneous Measurements

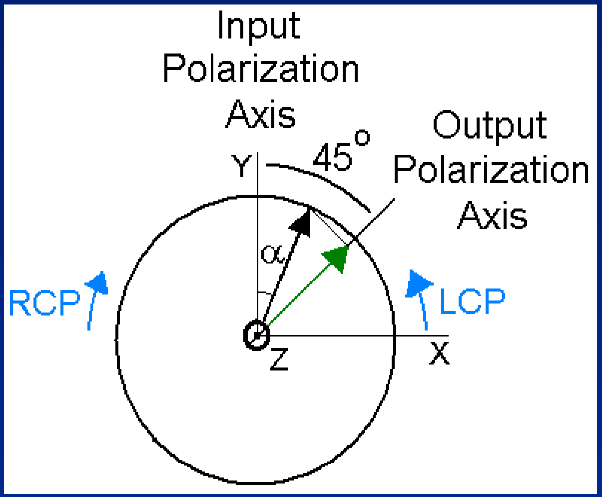


- Simultaneous measurements show an increase of 7°C in 11 min during which the output E-field is essentially constant.

Magnetic-Field Mapping via Magneto-Optic Sampling

- RF magnetic-field measurements based on Faraday effect





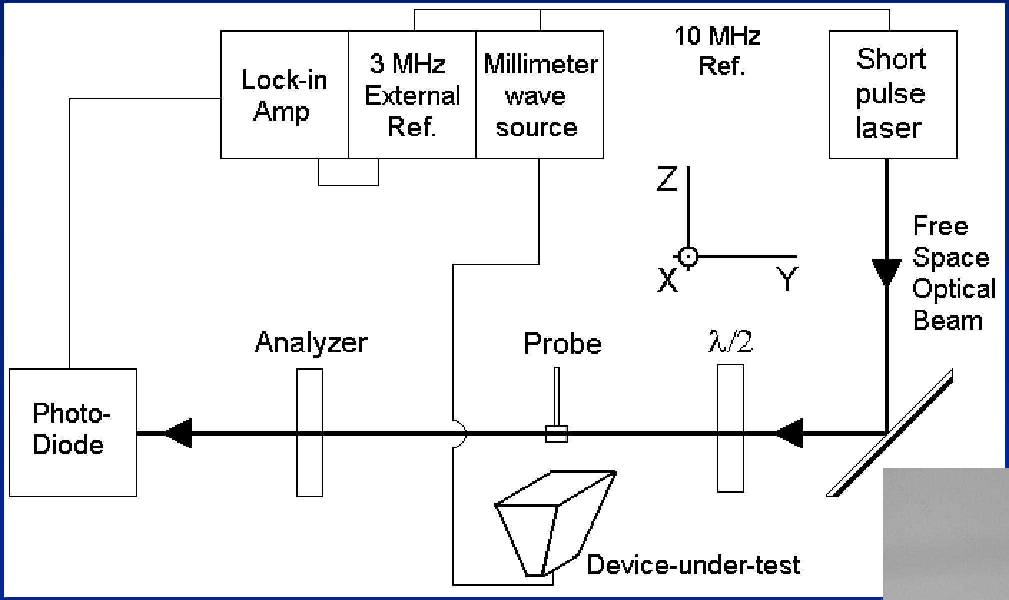
- External polarizers are oriented at 45 degrees.

$$T = \frac{1}{2} - \frac{1}{2}\sin(2\alpha)$$

$$\alpha = \mu_0 HVL$$

- Rotation of optical linear polarization due to magnetic field induced *circular* birefringence.

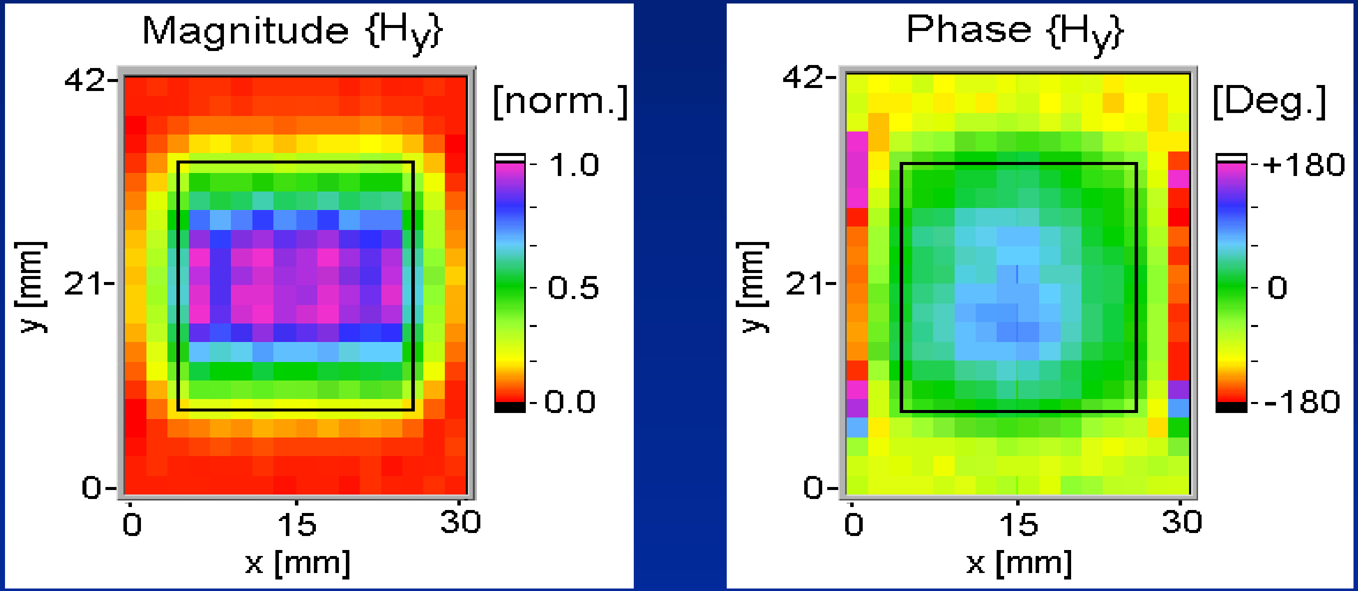
Magneto-Optic Magnetic-Field-Sensing System Schematic and Probe



Terbium Gallium Garnet (TGG) magneto-optic material

Magnetic-Field Sensing

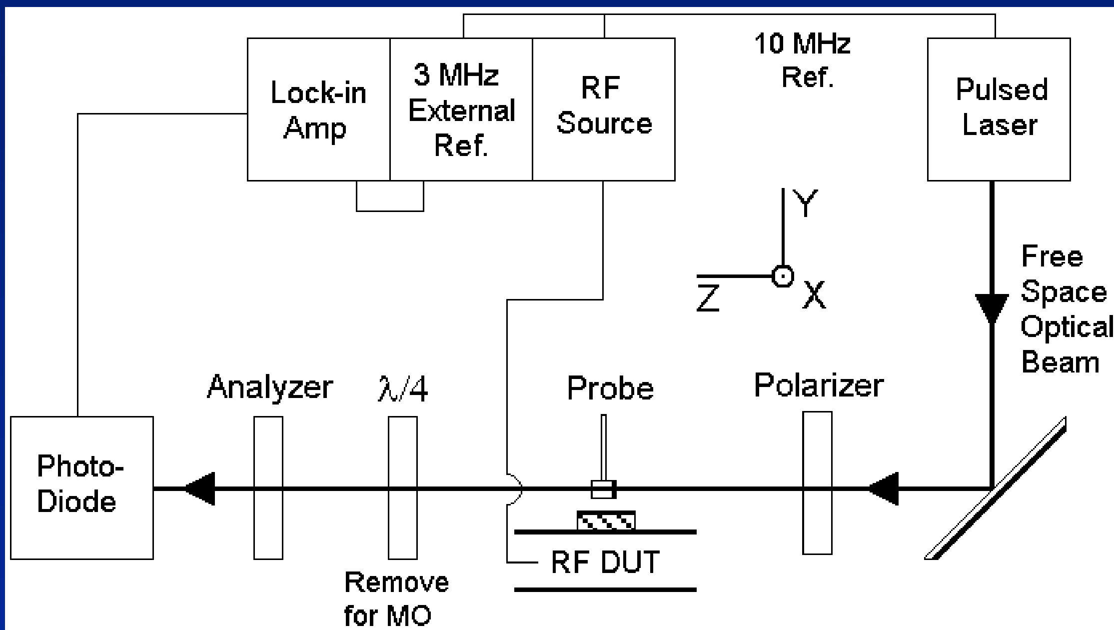
- Magnetic-field phasor vs. position of horn antenna aperture obtained at 60 GHz

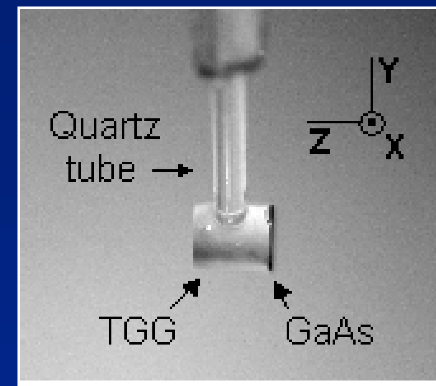


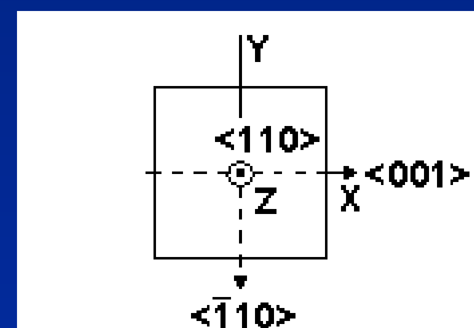
- Probe length tuned to device frequency to create resonant cavity and provide 10-dB sensitivity enhancement.
- B-field can be combined with E-field to determine impedance at internal measurement locations

Combined Electric/Magnetic-Field Sensor

- Utilizing a Hybrid Electro-Optic Magneto-Optic Probe







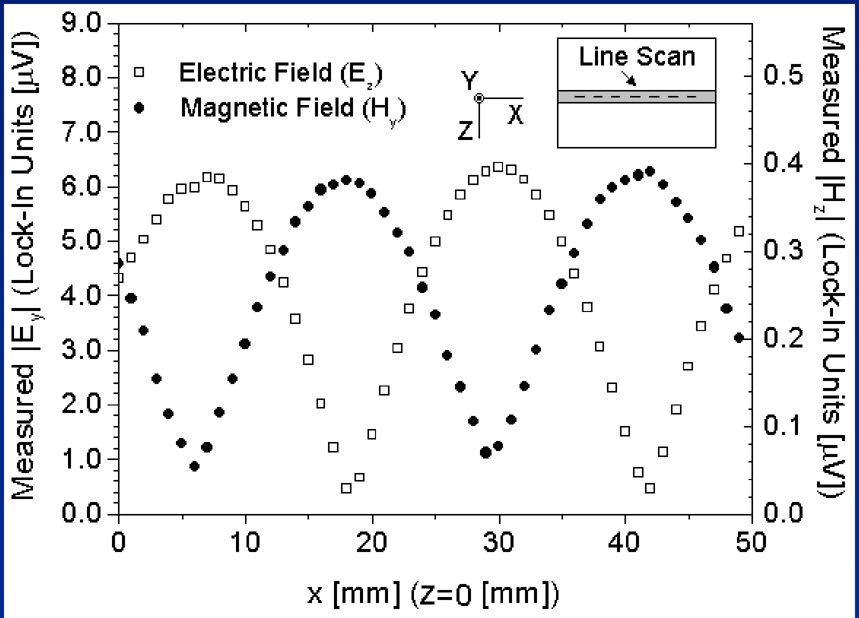
GaAs Crystal Orientation

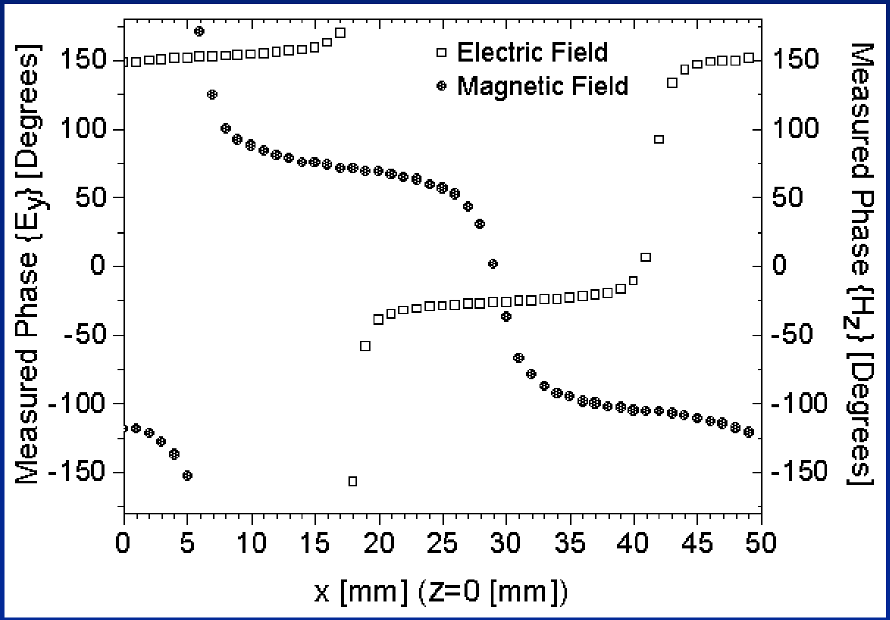
<u>TGG (ε_r=12.4)</u>
Diameter: 2 mm
Length: 2.3 mm
$V = 61$ rad T^{-1} m^{-1}

<u>GaAs (ε_r=13.2)</u>
Edge: 2 mm
Length: 0.1 mm
$r_{41} = 1.1$ pm V^{-1}

Hybrid EO/MO Sensor Measurements

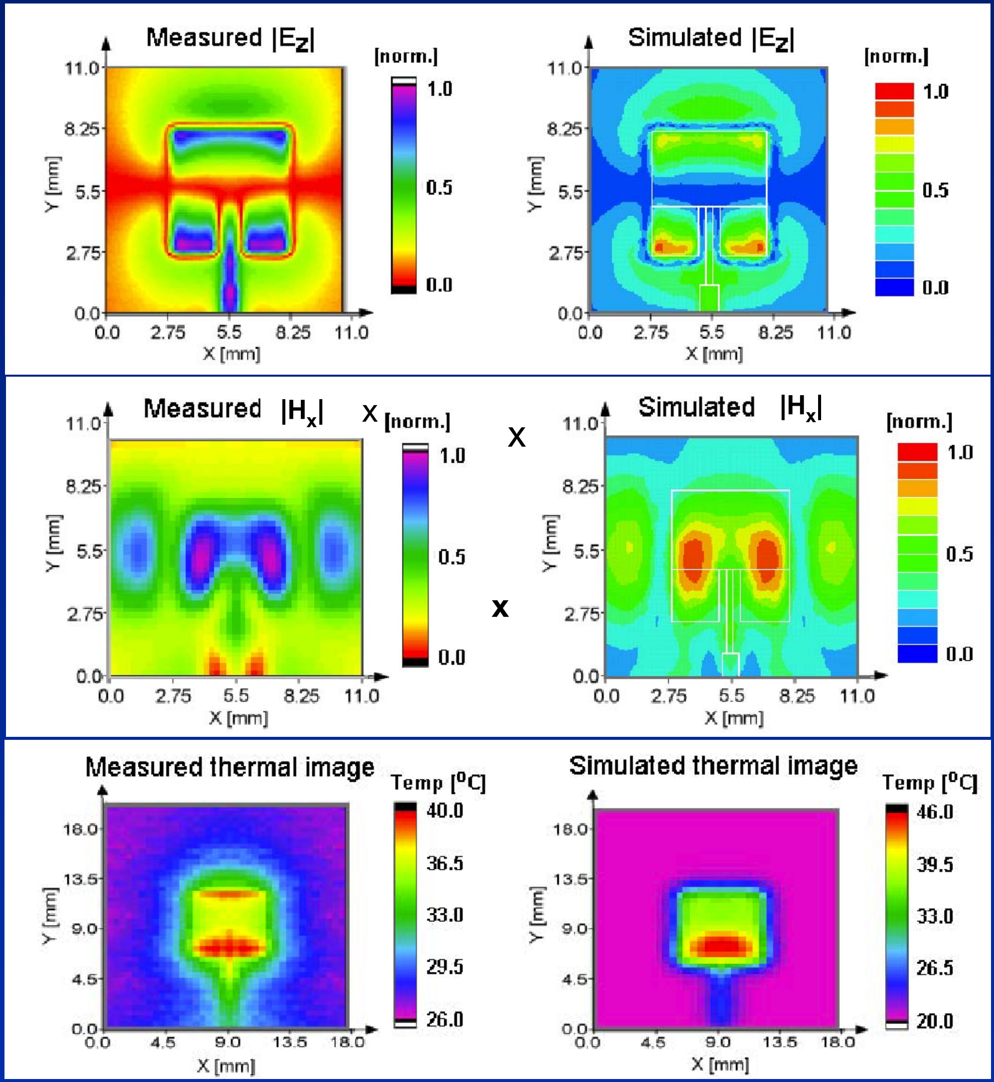
•Device-under-test: Shorted microstrip transmission line
•RF: 4.003 GHz @ 17.7 dBm





- Demonstrated 22 dB of isolation
- Isolation between electric and magnetic field sensitivity:
  - limited by degree to which electrooptic effect can be minimized
  - minimization driven by optical linear polarization purity

Electric-Field, Magnetic-Field, and Thermal Sensing in a High-Power Microstrip Patch



Conclusion

A fiber-optic-based field-sensing system offers:

- high spatial-resolution, broad-bandwidth, and low invasiveness
- detailed performance verification and diagnosis in the near-field region
- high measurement flexibility
- detection of electric field distributions inside of microwave enclosures and packages
- expanded capability with thermal and magnetic-field sensing