WIDEBAND TUNABLE PHASE SHIFTERS

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Abstract — Wideband tunable phase shifters are being developed using ferroelectric thin films for operation at room temperature. Pulsed-laser deposited thin films of $Ba_xSr_{1-x}TiO_3$ are being optimized to simultaneously possess a low loss tangent and reasonable modulation of the relative permittivity with an applied dc field. Preliminary devices based on a 1-cm long coplanar waveguide have resulted in 120 degrees of differential phase shift at 20 GHz on an MgO substrate.

In order to mitigate the deleterious effects, on impedance match, of modifying the capacitance per unit length, ferroelectric/ferrite structures are being developed which will make it possible to independently tune both the inductance and capacitance per unit length. In principle, this will permit tuning of the phase velocity while maintaining the transmission line characteristic impedance. $Ba_xSr_{1-x}TiO_3$ has been deposited on YIG and maintains desirable tuning characteristics.

Motivation for Employing Ferroelectrics for Phase Shifters

- Ferroelectrics are a dielectric material and thus do not conduct:
  - very low (practically nonexistent) current draw means low power
  - transient current requirements will be determined by switching speeds required
  - very low dc dissipation and hence low heat load
- Material induced dispersion is practically non existent for most (not all) ferroelectrics:
  - broadband phase shifter designs limited only by
  - VSWR due to characteristic impedance variation
  - choice of waveguiding geometry
- High relative dielectric constant:
  - small space efficient circuits due to small wavelength in device
  - appropriate for receive applications (or transmit, if prior to power amp)

Design Trade-offs of Tunable Ferroelectric Coplanar Waveguide Phase Shifters

- Offer continuously variable true time delay:
  - the reciprocal of frequency is the time required for one full cycle of a wave
  - $\Delta T \text{ (ns)} = \left\{ 1/f(\text{GHz}) \right\} \times \left\{ \Delta f(\text{degrees})/360 \right\}$
- Effects of a large dielectric tuning yielding a large change in capacitance are:
  - Phase velocity: $v_p = \left\{ 1/LC \right\}^{1/2}$
    - large change in phase velocity resulting in
    - compact structure for 360° of phase shift with
    - minimum attenuation losses
  - Characteristic impedance: $Z_c = \left\{ L/C \right\}^{1/2}$
    - large change in characteristic impedance resulting in
    - larger impedance mismatch
    - larger mismatch losses
- Design trade-offs must be optimized for specific application
- Broadband phase shifter designs will be harder to realize

Issues and Challenges Affecting Combining Ferroelectrics and Ferrites for Tuning Microwave Devices

- In principle, independent control of the capacitance and inductance per unit length allows great flexibility:
  - characteristic impedance can be tuned to a constant value while still varying the phase velocity
    - ideal for tunable delay lines and phase shifters
    - useful for tunable filter applications
  - electrical length can be held constant while the characteristic impedance is tuned
    - useful for tunable filter applications
- Disadvantages include:
  - Complexity of the materials and deposition processes
  - Tuning speed of resultant device is limited by material with the slowest tuning mechanism — the ferrite
  - Loss of resultant tunable device is limited by the most lossy material present — the ferroelectric
- Finding optimum materials combinations and circuit design will be a challenge

Summary of Results

- Measurements on a mismatched 1 cm-long CPW transmission lines using both MgO and $LaAlO_3$ substrates:
  - 33.3 ps differential time delay using $LaAlO_3$ substrate
    - from $\sim 4\,{}^{2}/_{3}\ \lambda$ long at 0 V bias to $\sim 4\ \lambda$ long at 150 V bias
  - 16.7 ps differential time delay using MgO substrate
    - from $\sim 2\,{}^{1}/_{3}\ \lambda$ long at 0 V bias to $\sim 2\ \lambda$ long at 150 V bias
- Measurements on a nearly matched 0.85 cm-long CPW transmission line on MgO with wider gaps and modified transitions:
  - effect of tuning on the match is readily apparent
  - total tuning is relatively small due to low applied DC field
    insertion loss of ~ 7.5 dB at 20 GHz
- Measurements on a mismatched 1 cm-long CPW transmission line on BST on YIG with a GGG substrate
  - similar tuning of phase velocity is achieved with modest E-field and/or B-field bias
  - insertion loss of ~ 6-7 dB from 10-12 GHz

Conclusions

- Considerable progress has been made in realizing ferroelectric materials for wideband phase shifter applications:
  - design of transitions and tunable impedance matching structures will be needed to realize broadband designs
  - measured losses are encouragingly low for such unoptimized designs
  - optimized designs should perform equal or better than the conventional state-of-the-art
- Initial measurements of simultaneous tuning of layered ferrite/ferroelectric CPW transmission lines is encouraging:
  - CAD tools to realize practical structure impedance matched structures are not commercially available
  - Iterative approach for realizing impedance matched devices will be time consuming but will also result in useful test case data as tools are developed
  - similar E-field and B-field tuning sensitivities can be realized with structures which are compatible with high quality materials deposition and good microwave design

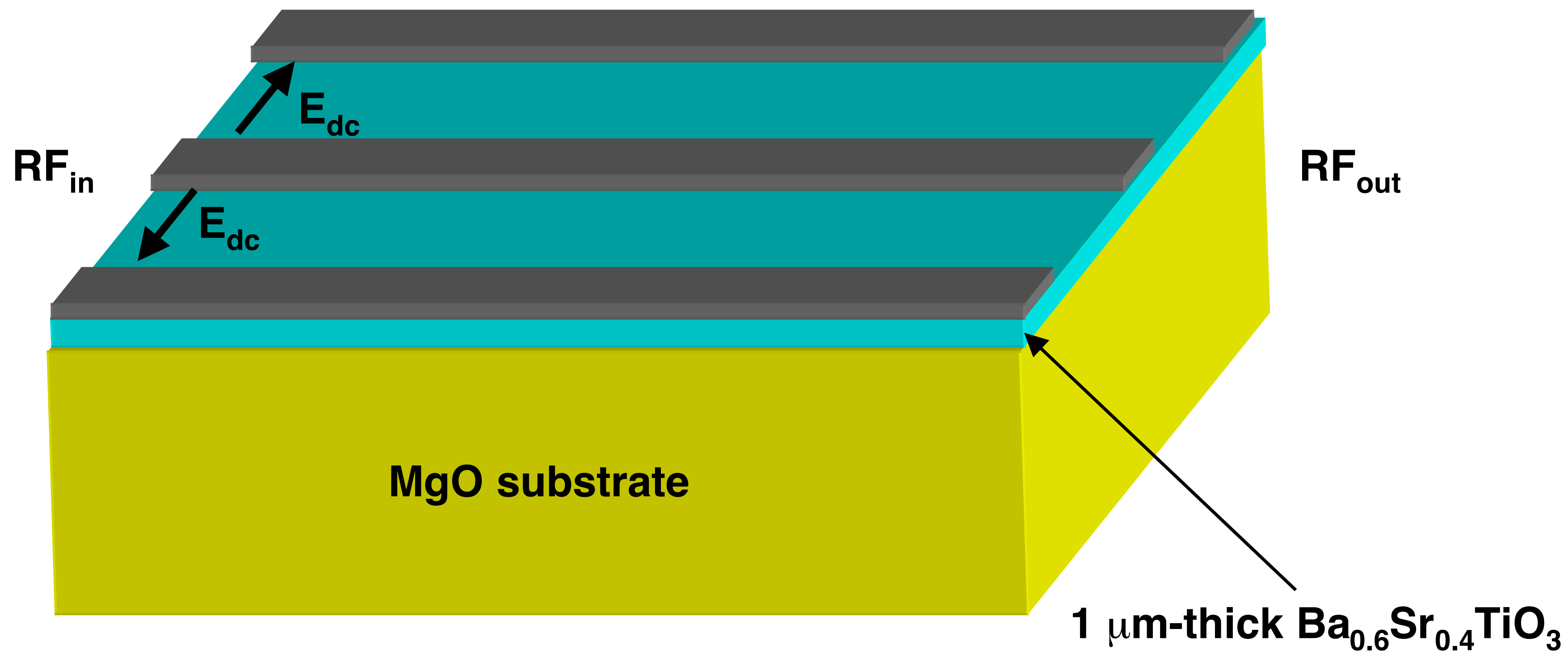
Plans

- Continue refining deposition techniques to improve microwave properties of deposited thin-films
- Complete measurements of existing ferroelectric/ferrite CPW lines
  - investigate behavior as bias orientation is changed
  - measure response under large magnetic field biases
- Second generation CPW mask set has been designed and made
  - greater flexibility in ability to modify characteristic impedance by modifying cross section
  - expected improvement in device yield
  - iterate as needed to develop impedance matched designs
- Investigate circuit-based CAD/CAM for parameter extraction from measured data
- Full-wave modeling of both ferroelectric CPW structures and ferroelectric/ferrite CPW structures for impedance matched devices

Broadband Electric Field Tuning of the Phase Velocity Of a Coplanar Waveguide Transmission Line

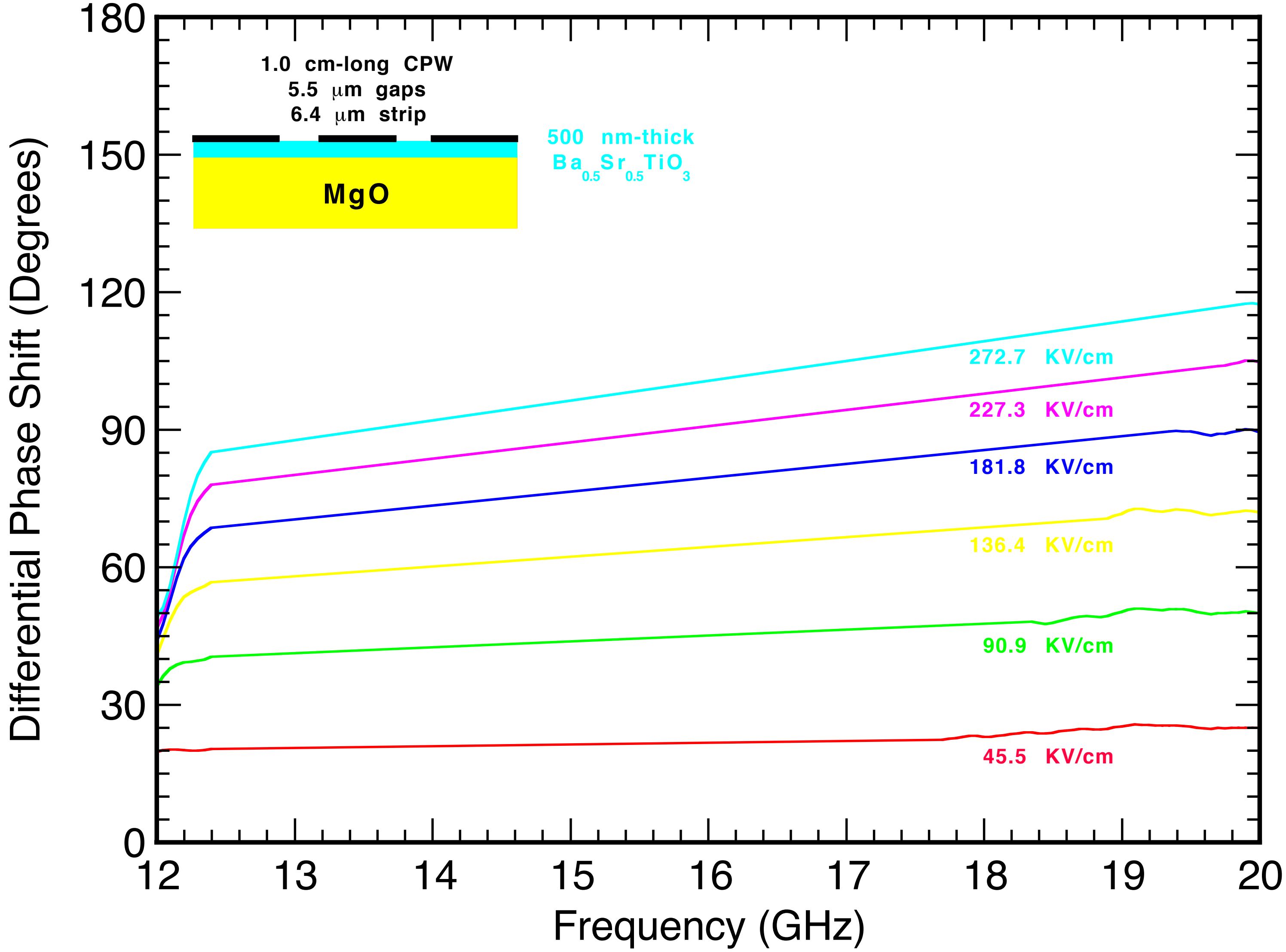
Schematic of the Coplanar Waveguide Transmission Line Being Developed for Electronically Tunable Wideband Phase Shifters

- Electric field bias is provided by applying a voltage between the center conductor and the outer (ground) conductors
- Promising results have also been obtained using $LaAlO_3$ substrates



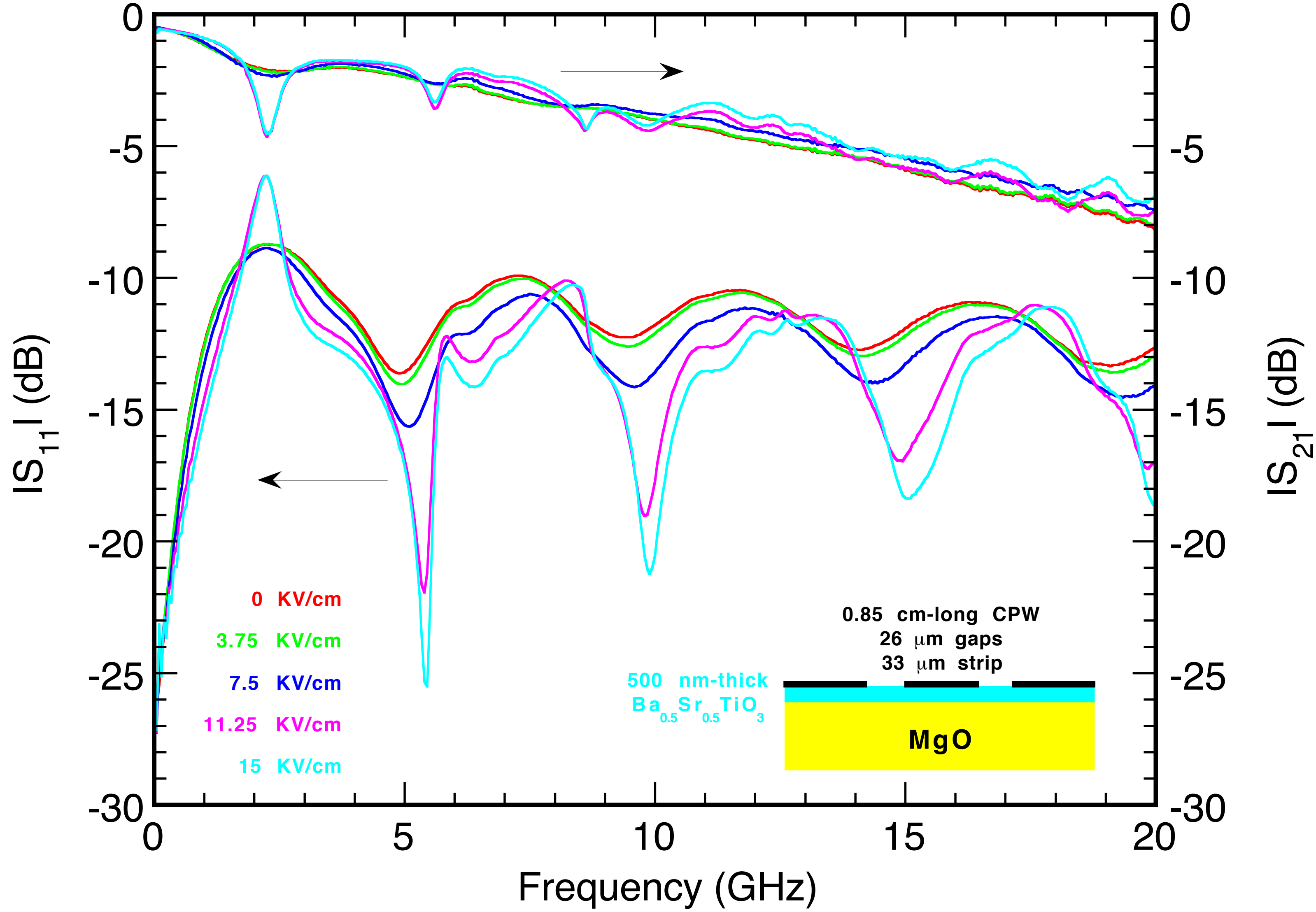
Broadband Electric Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

Measured Differential Phase Shift Versus Frequency and Bias for a Low Impedance 1 cm-long Coplanar Waveguide with Narrow Gaps



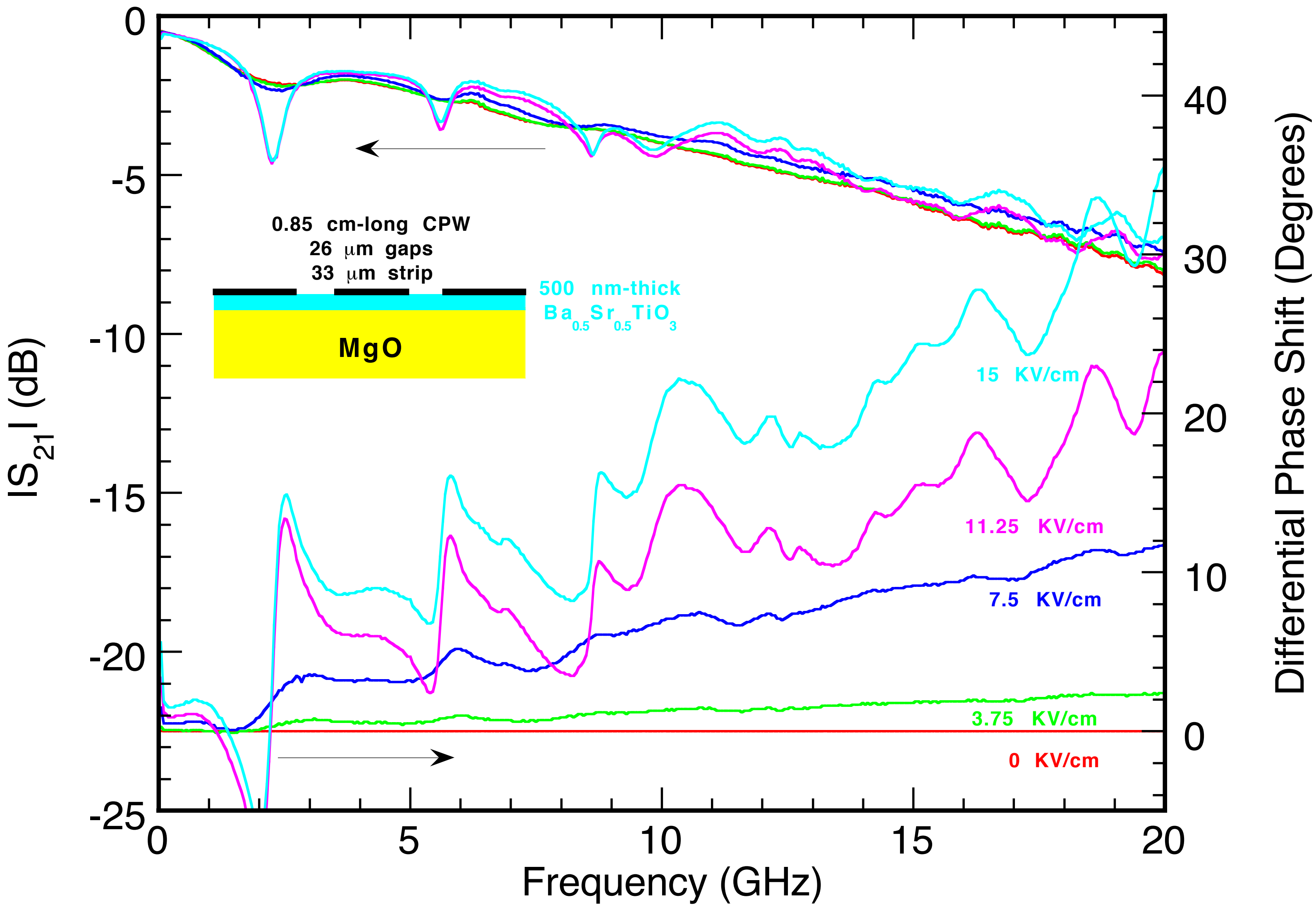
Broadband Electric Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

Insertion Loss and Return Loss versus Frequency and Electric Field Bias for a CPW with Wider Gaps and Improved Match



Broadband Electric Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

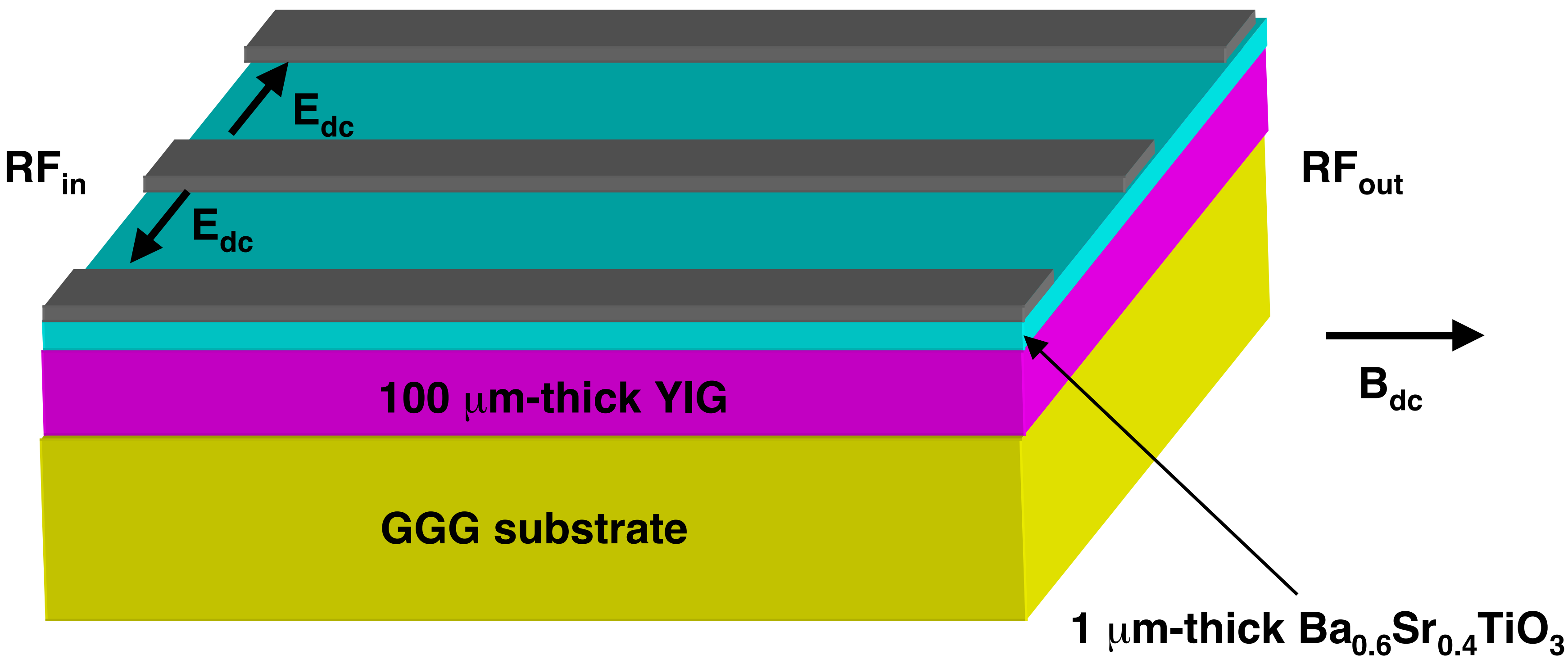
As the Phase Velocity is Modulated with the E-field Bias, the Match to the Transmission Line Degrades Limiting Bandwidth



Electric Field and Magnetic Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

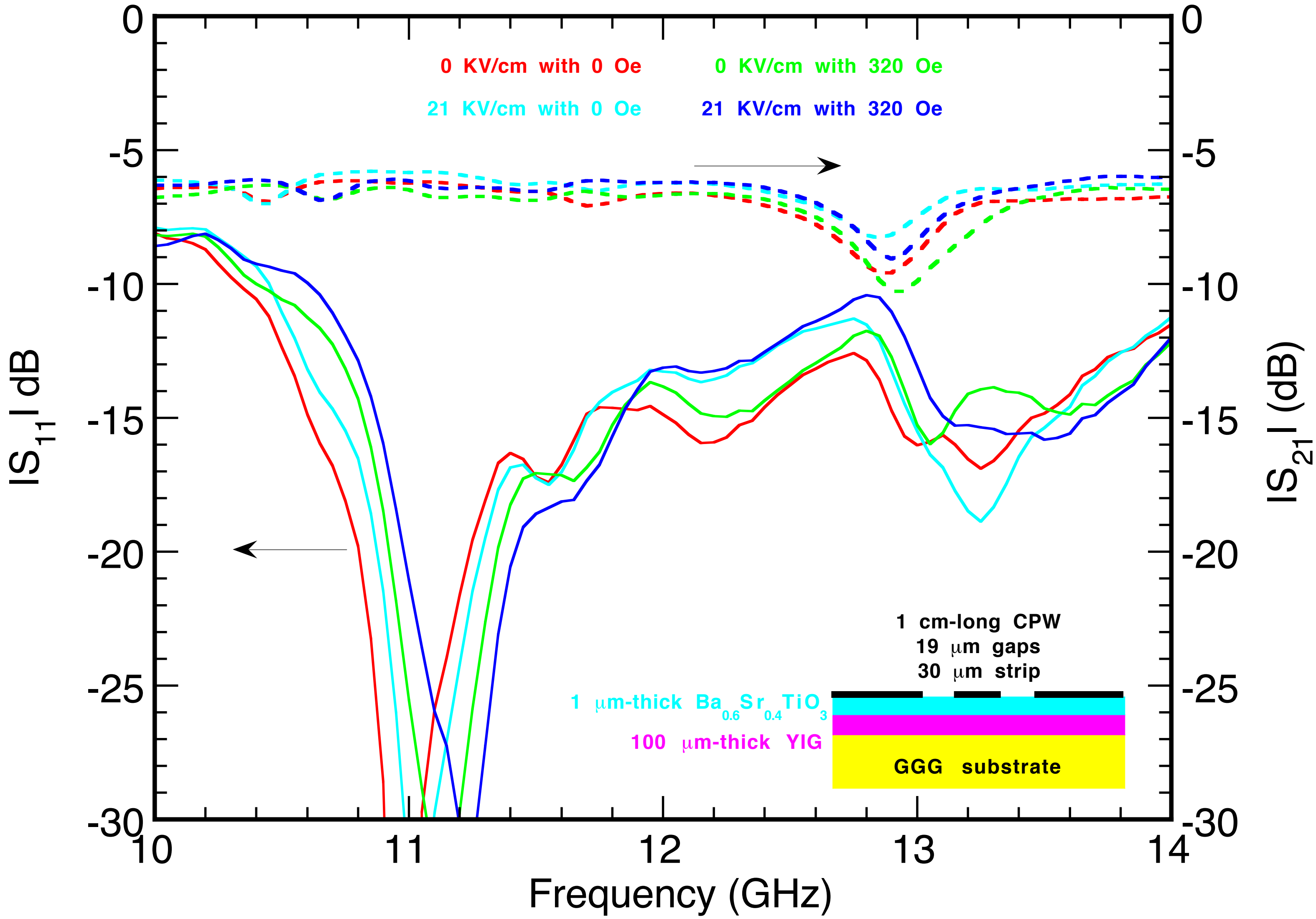
Schematic of the Structure Fabricated for Measuring Simultaneous E-field and B-field Tuning of the Phase Velocity

- Electric field bias is provided by applying a voltage between the center conductor and the outer (ground) conductors
- For convenience in the laboratory, magnetic field bias is provided by an external electromagnet



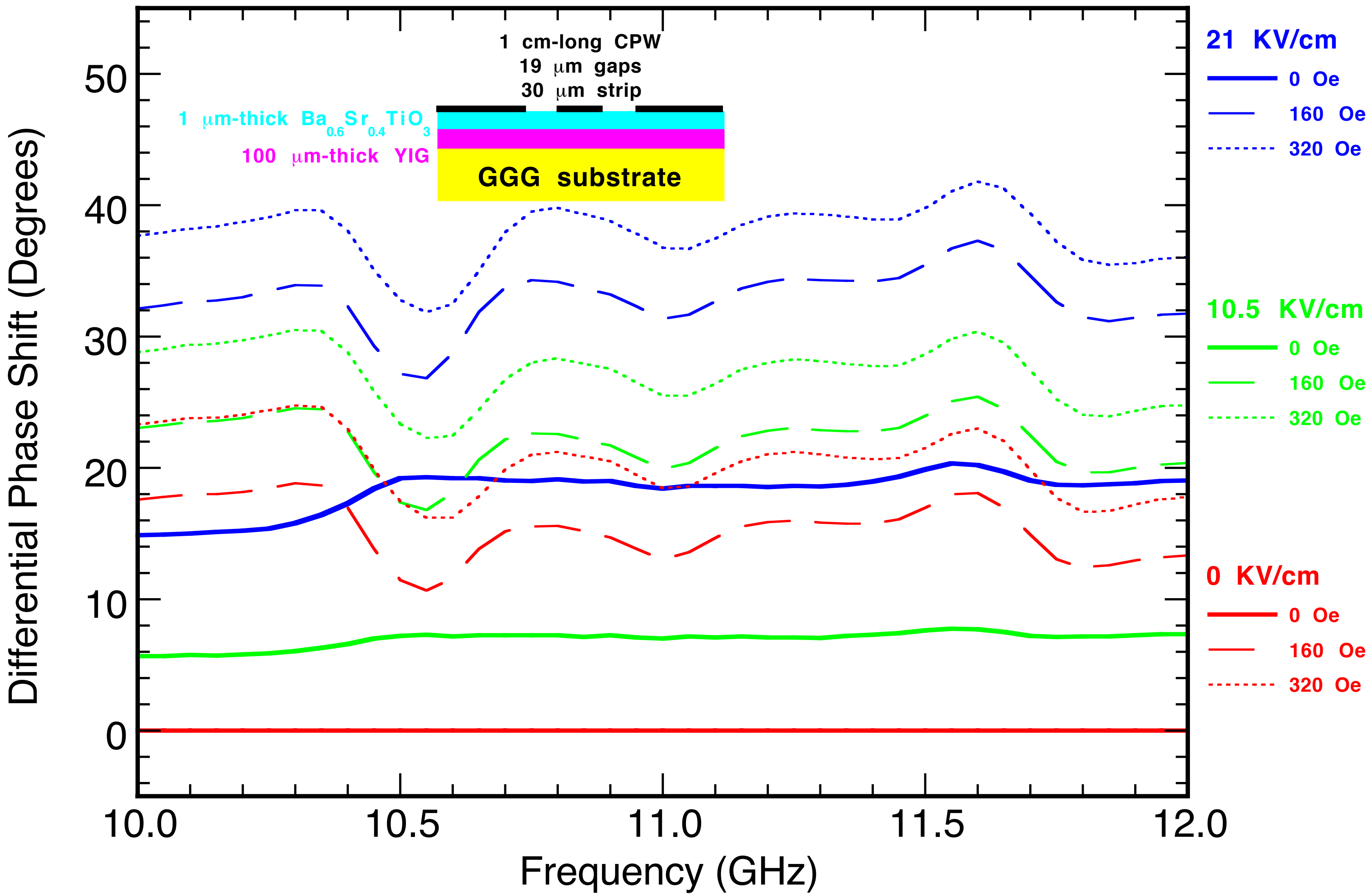
Electric Field and Magnetic Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

Insertion Loss and Return Loss for the Extremes of Electric and Magnetic Field Biases Applied



Electric Field and Magnetic Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

Differential Phase Shift as Calculated From Measured Data for Various E-field and B-field Bias Conditions



Electric Field and Magnetic Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line

First Order Behavior of the E-field and B-field Tuning was Determined from a Linear Fit to the Measured Differential Phase Shift Data