Compact, Physics based Model for Nonlinear RF Magnetics encompassing EM and Spin Waves

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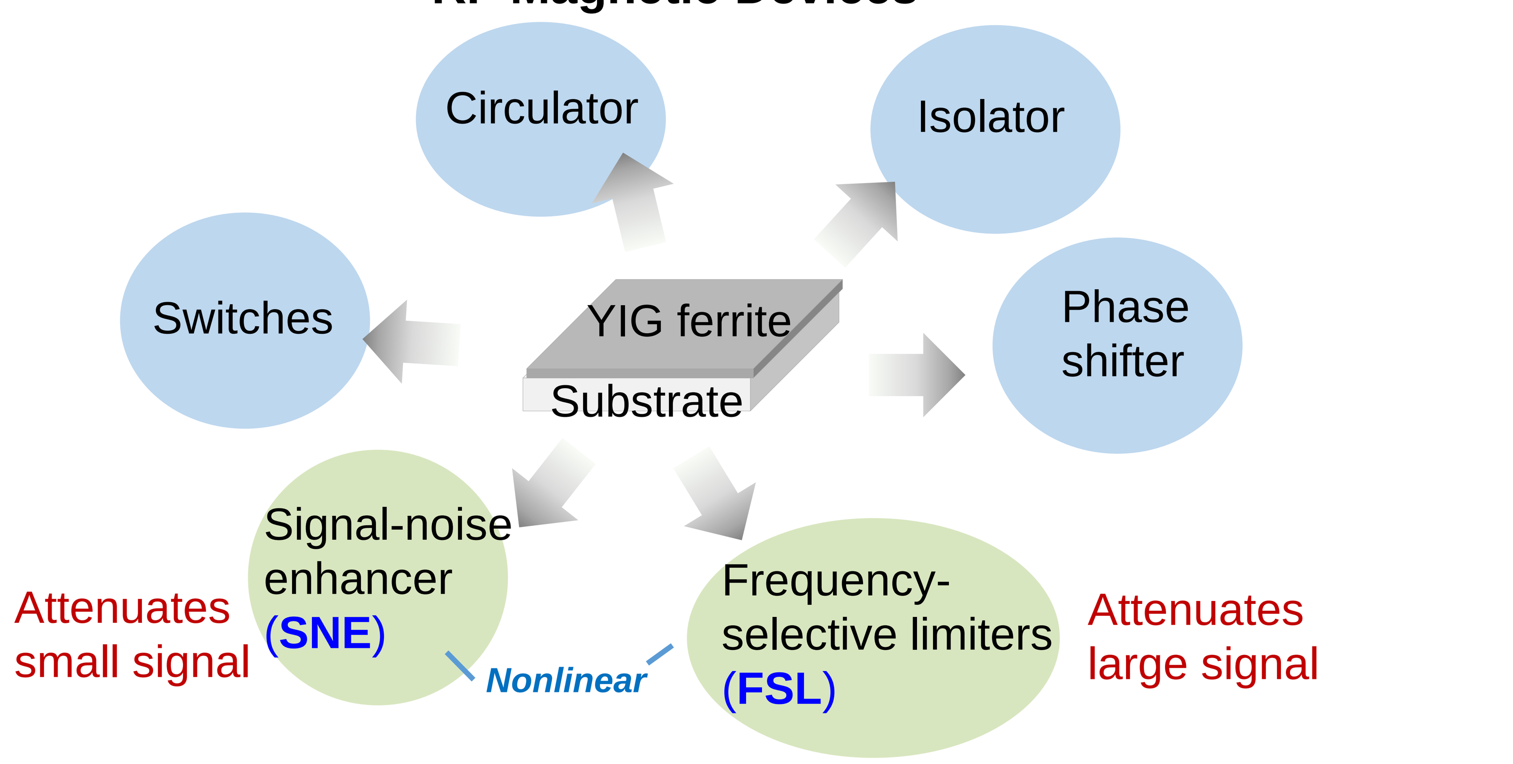
M3IC: Magnetic Miniaturized and Monolithically Integrated Circuits

5G and Future RF

Background

- RF Magnetic devices are extensively used in DoD applications and they offer functions that are beyond what traditional electronics can offer, such as non-reciprocal, high-power and nonlinear signal processing directly in RF domain.

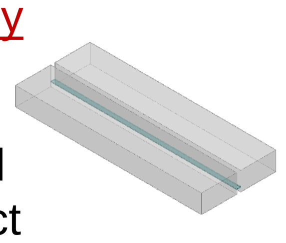
RF Magnetic Devices



- Nonlinear RF magnetic devices such as Frequency Selective Limiters (FSL) and Signal to Noise Enhancers (SNE) can be used to notch out strong jamming without hurting the sensitivity of the RF receiver.
- Current modeling tools do not accurately capture the fundamental physics of these components; limiting system design optimization.

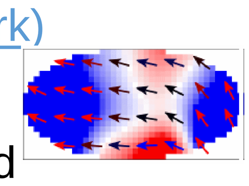
Limitation of Current Modeling Tools:

HFSS (High Frequency Structure Simulator)



✓Full wave EM model
✓Good for large object
! Missing magnetics physics (no exchange coupling etc.)
! Nonlinear behavior cannot be captured

OOMMF (Object Oriented MicroMagnetic Framework)



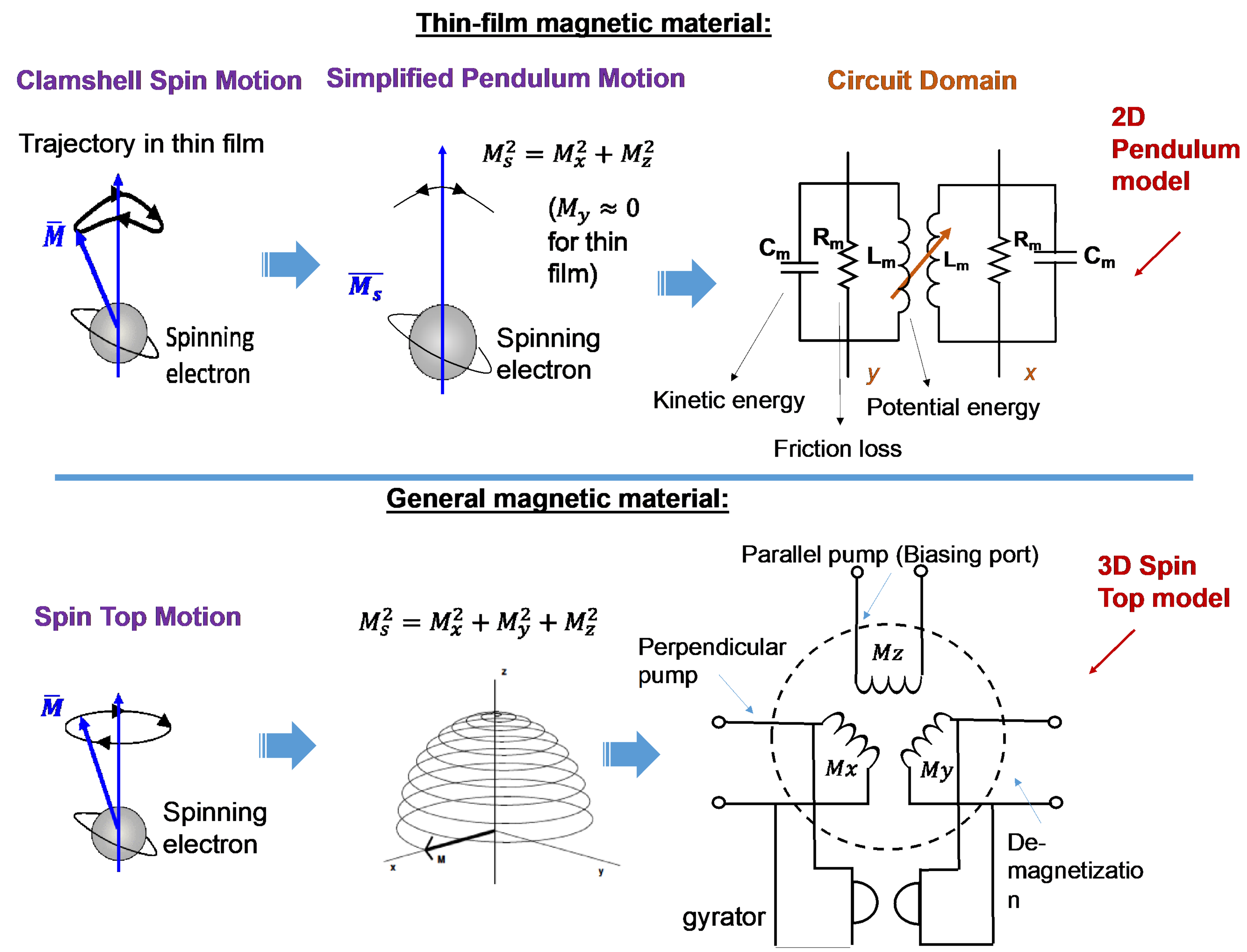
✓Micromagnetics model
✓Inclusion of sophisticated magnetics physics
! Only good for small dimension (< 100 μm)
! Not compatible with system design

- The goal of this program is to develop a precise yet computationally affordable model of nonlinear RF magnetic devices that will allow system engineers to use for design of RF systems with such devices.
- For accuracy, it requires capturing the full-wave physics defined by Maxwell's equations, the nonlinear magnetics physics defined by Landau-Liftz-Gilbert equation, certain quantum mechanical physics such as exchange coupling and interplay among all the above.
- Representing foundational electron spin physics by nonlinear circuit model through their mathematical/physical analogy which reduces the complexity, increases stabilities, provides easy interface with electromagnetics physics and is compatible with system circuit simulators.

Approach

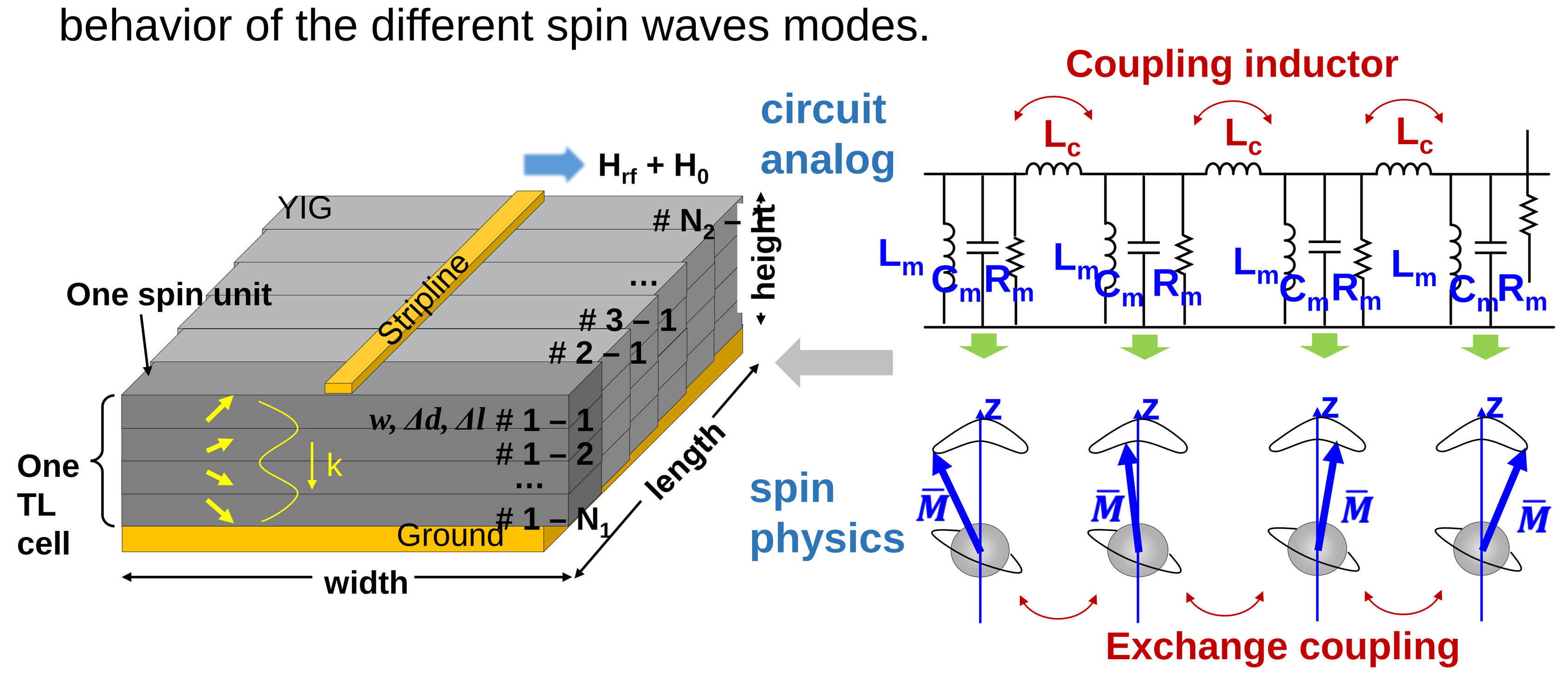
- Proposed modeling approach consists of three key steps, e.g. (1) creating nonlinear circuit units for fundamental spin motions (2) connecting those units with coupled inductors or resonators to represent exchange coupling in spin waves (3) inserting the resultant circuit models into transmission line model to interface with EM waves.

Equation of motion: $\frac{dM}{dt} = -\mu_0 \gamma M \times H$



Inclusion of Spin Waves, scale up and interface with EM waves

- The coupling of spins (magnetostatic coupling & exchange coupling) create spin waves which are the main mechanisms for frequency selective power limiting.
- Exchange coupling is represented by coupled inductors or resonators in parallel or penpendicular spin modes as governed by the dispersion behavior of the different spin waves modes.

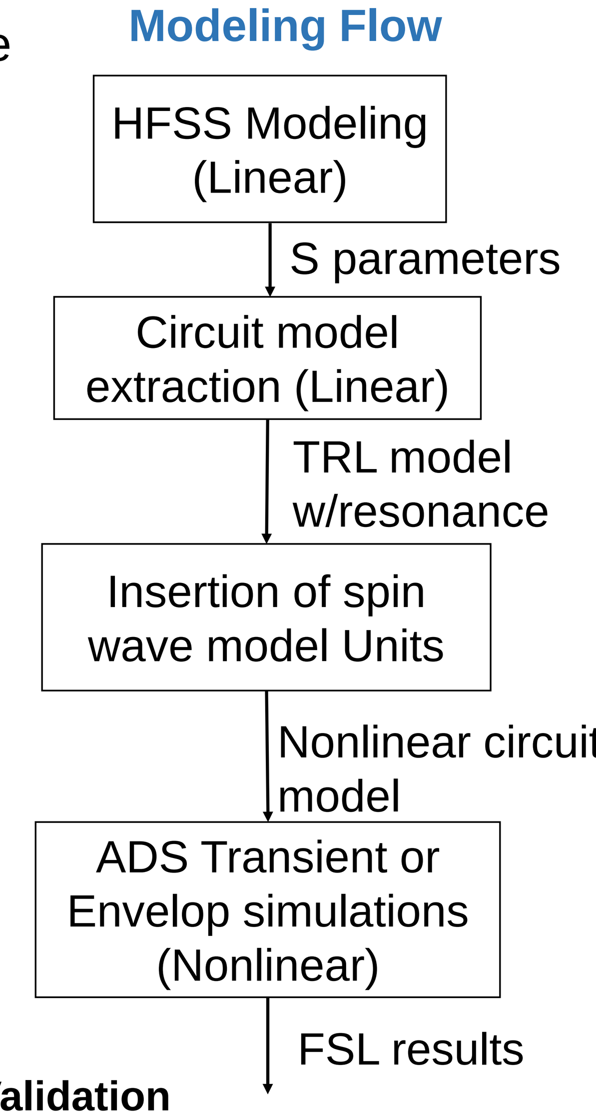


- Spin wave models then are scaled up to couple to an EM wave transmission line to predict the real device behavior, through cascading multiple sections of circuit units with magnetic flux continuity.

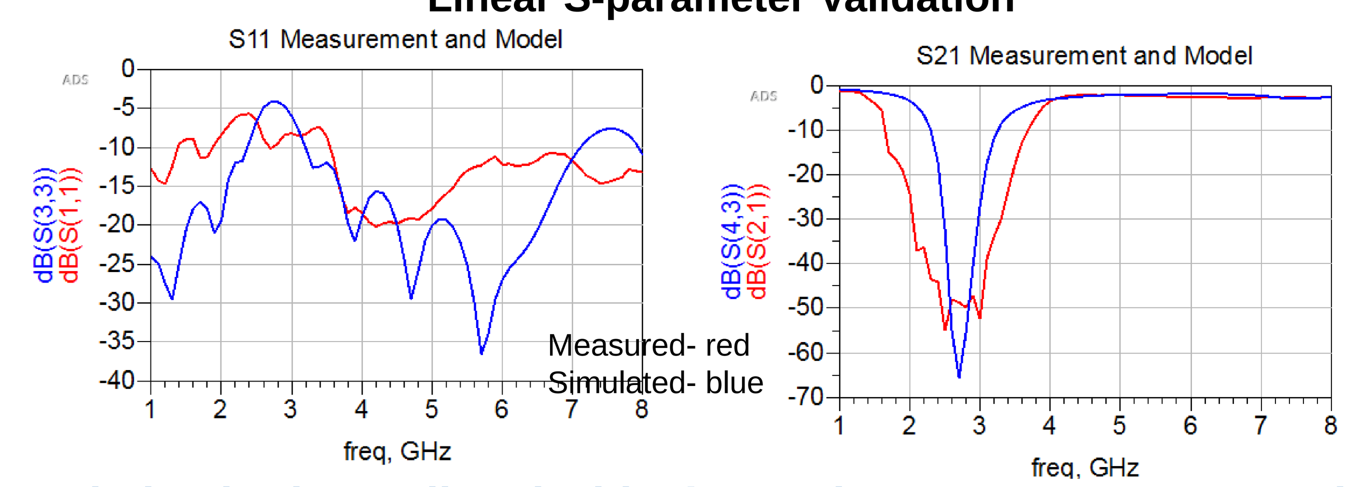
Results and Impact

- Proposed model is compared against the measured results of a C-band CPW based FSL device.
- Circuit model is generated in Advanced Design System (ADS) following the flow on the right, including both parallel and perpendicular spin modes.
- Simulation results for 4-6 GHz, 5-20 dBm input (6 x 300 nonlinear spin wave elements) agree very well with the measured results, with <0.5dB discrepancy in linear behavior and <1dB error in nonlinear behavior of FSL operating region.
- This is the first time such a physics based model is developed without going through curve fitting to the experimental results.

Modeling Flow

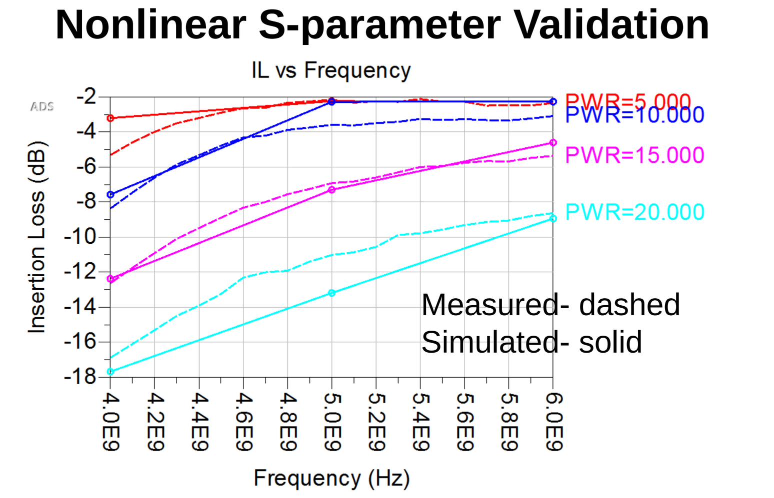


Linear S-parameter Validation

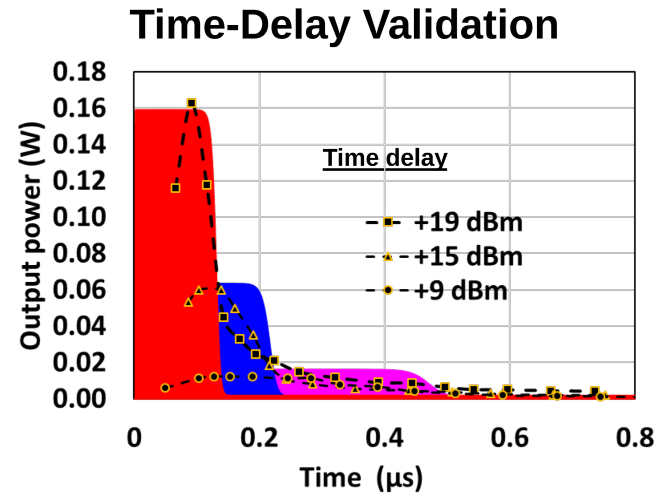


Linear behavior is predicted with almost the same accuracy as what HFSS can do (HFSS is used to establish the baseline).

Nonlinear S-parameter Validation



Time-Delay Validation



Nonlinear behavior is well predicted by proposed model and HFSS would completely miss this power dependency and time-delay response, while OOMMF would take years and supercomputers to model such behaviors.

Impact

- A nonlinear physics based compact model is developed for nonlinear RF magnetic devices such as FSL for the first time.
- The model precisely predicts key factors of FSL devices including power attenuation, threshold, insertion loss, frequency selectivity, and time delay and is ready to plug into the system design software (ADS) by DoD users.
- FSL devices based systems, if optimized with this model, will offer tremendous amount of potential for anti-jamming, adaptive filtering in military radios and interference protection for commercial wireless systems.

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