Electrically Tunable Miniaturized Frequency Selective Surface with Smart Engineered Substrate

Jinqun Ge, *Student Member, IEEE*, and Guoan Wang, *Senior Member*, IEEE

***Abstract*—This report presents an enabling technology with wide frequency-agile capability and design flexibility from the unique perspective of smart material. A novel engineered substrate enabled with multilayers of ferromagnetic thin films is developed. Permalloy (Py) thin films are selectively patterned on a normal dielectric substrate, resulting in both high permittivity and permeability. In addition, the permeability of the ferromagnetic thin films is tunable with the static magnetic field generated by the applied DC biasing current. An accurate model is developed to analyze and optimize the proposed engineered substrate. Finally, a frequency selective surface is designed on the engineered substrate, providing further miniaturization, enhanced performance, and wide tunability.**

***Index Terms*—Electrically tunable, engineered substrate, frequency selective surface (FSS), permeability.**

I. Introduction

THE fastest-growing wireless communications market has seen dramatic changes in both the requirements on, and the capabilities of the radio to support wireless connections. As the ever-increasing demand for wireless technologies ratchets up the need for spectrum resources, efficient spectrum reconfigurability and flexibility is gaining new interest as a strategy to make efficient use of the available airwaves. Reconfigurable wireless networks aim at enabling "intelligence" into the existing system to perceive and assess the available resources, to autonomously learn to adapt to the dynamism in the wireless environment, and to reconfigure its operating mode to maximize the utility of the available resources. Therefore, with the help of reconfigurable wireless networks, the problem of huge spectrum scarcity can be addressed.

Although technical solutions for reconfigurable radio architectures have been widely studied and successfully demonstrated, current technologies have limitations in providing a wide continuous tunability range, flexibility, and power handling capability. This report presents an enabling technology with wide frequency-agile capability and design flexibility from the unique perspective of smart material. An electrically tunable engineered substrate is developed by patterning Permalloy (Py) thin films inside a normal RF substrate [1-4]. The additional magnetic loss and ferromagnetic resonance (FMR) frequency of the engineered substrate are improved by patterning the ferromagnetic films with selectively sizes and aspect ratios. By applying DC current, the permeability of Permalloy thin films can be tuned, resulting in the permeability tunability of the engineered substrate. Arbitrary RF and microwave components could be developed on the proposed engineered substrate, providing further miniaturization, enhanced performance, and wide tunability. In this report, a frequency selective surface (FSS) is designed on the engineered substrate to demonstrate the design efficacy.

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II. Project Outcome

As shown in the insert of Fig. 1, a simple 50Ω microstrip line with patterned Permalloy inside the substrate is simulated. Based on the transmission theory, the increased effective permeability of the engineered substrate can be characterized by the extracted inductance. And the relationship between the effective permeability of substrate and the extracted inductance of microstrip is also derived as a fitting function of $F(x)$ in this research. In Fig. 1, the extracted inductance of different Py pattern dimensions shows that the effects of the Py patterns can be ignored when the pattern size is smaller than 0.02% λ_0, where λ_0 is the wavelength in free space.

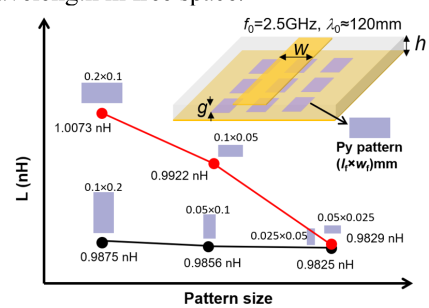

Fig. 1. Pattern effects on the permeability of the engineered substrate.

Based on this, the single layer of Py patterns can be considered as an equivalent substate with increased permeability. As illustrated in Fig. 2, a multilayer substrate model is developed to calculate the effective permeability of the engineered substrate.

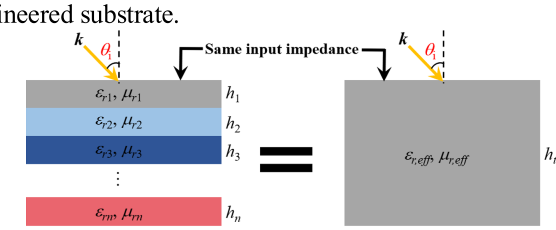

Fig. 2. Multilayer substrate model.

The effective permeability of a multilayer substrate can be calculated by

$$\mu_{r,eff} = \sum_{n=1}^{N} \frac{\mu_{rn} h_n}{h_t} \times k_{\mu_{r1}} \times k_{\mu_{r2}} \times k_{\mu_{r3}} \quad (1)$$

where $k_{\mu r1} = F\{f(g/h)\}$, $k_{\mu r2} = F\{f(t)\}$, $k_{\mu r3} = F\{f(\eta)\}$. $k_{\mu r1}$, $k_{\mu r2}$, and $k_{\mu r3}$ are the fitting factors that describe the effects of the vertical position of the Py layer (g/h), Py layer thickness (t), and the filling density of the Py layer ($\eta = A_{Py}/A_{unit}$), respectively. The simulated results of the engineered substrate under different scenarios are shown as the black lines in Fig. 3, which work as references. All of these simulations are conducted within a unit cell, which is defined as the effective area where Py patterns have effects on the extracted inductance. On the other hand, the red lines show the results calculated by the multilayer formula without the corresponding fitting factors. Thus, the fitting functions $f(g/h)$, $f(t)$, and $f(\eta)$ are derived as:

$$f\left(\frac{g}{h}\right) = 0.13\left(\frac{g}{h}\right)^2 - 0.24\left(\frac{g}{h}\right) + 1.02 \quad (2)$$

$$f(t) = 1 \quad (3)$$

$$f(\eta) = 0.51\eta + 0.51 \quad (4)$$

$f(t) = 1$ is because the thickness effects are already considered in the original multilayer substrate formula. In addition, Fig. 3 (c) shows that the effects of layer numbers can be considered as the increase of total Py thickness (t), and the effects of the vertical positions are mainly determined by the first layer near the signal line.

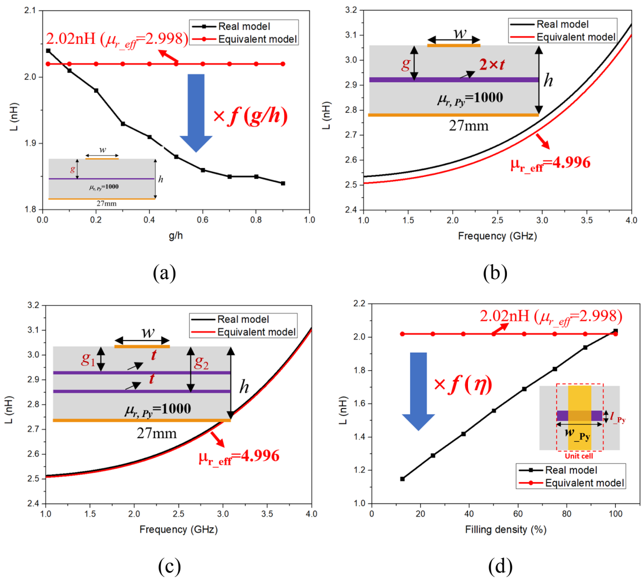

Fig. 3. Extraction of fitting factors: (a) thickness, (b) layers, (c) vertical positions, (d) filling density.

The developed engineered substrate model is used to predict the configuration of an engineered substrate for a specific permeability. As shown in Fig. 4 (a), a ten-layer Permalloy thin films enabled engineered substrate is optimized to provide an effective permeability of 2.34. Each layer of the Py thin films consists of 100 nm thick Py in an array of 15 µm × 20 µm pattern sizes with 10 µm gaps among them. Gold lines are also implemented beneath the Py patterns for biasing DC current. A square-ring based FSS is put on the top of the engineered substrate to achieve miniaturization and tunable operating frequency. By comparing the performance of the miniaturized FSS and FSS on the substrate without Py patterns, the same performance can be found in Fig. 4 (b), but a 16.02% size reduction is achieved by the FSS on the engineered substrate. In addition, the effective permeability of the engineered substrate can be tuned from 2.34 to 2.02 by biasing DC current from 0 mA to 500 mA, resulting in the operating frequency of the FSS changing from 2.45GHz to 2.67GHz.

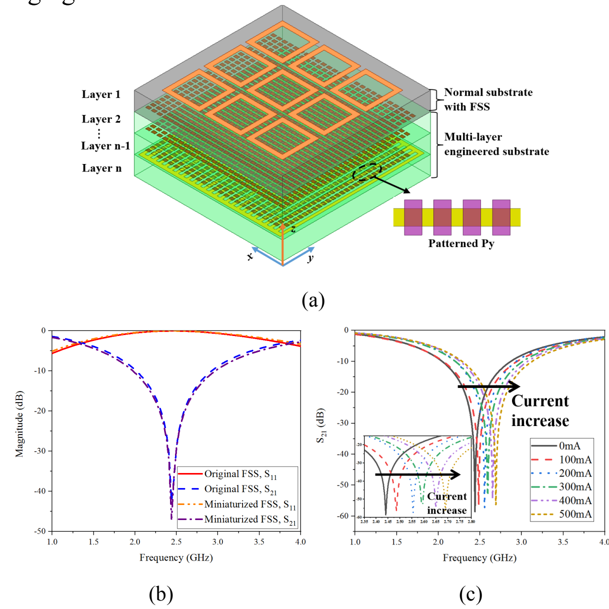

Fig. 4. (a) FSS on the proposed engineered substrate. (b) Results comparison. (c) Performance of FSS on engineered substrate under different DC biasing conditions.

Other RF components, such as planar filter, phase shifter, and ultra-wideband (UWB) antenna, are also implemented on the proposed engineered substrate to demonstrate the efficacy and benefits. In particular, the increased permeability can increase the bandwidth of an antenna, which shows the promising prospect of the smart engineered substrate [3].

III. Career Plan and Fellowship Impact

I am now preparing my thesis to finish my doctoral studies. After graduation, I will start a postdoctoral position and keep working closely with the MTT-S community. This award is a true honor, and it has given me the confidence, motivation and visibility that I needed to keep pursuing revolutionary research and connecting with others. I look forward to participating in future events hosted by the IEEE MTT-S society.

Acknowledgment

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