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Characterization of Thin Film Enabled Engineered Substrate for RF Applications

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***Abstract*—Engineered substrate enabled by Permalloy ($Ni_{80}Fe_{20}$, Py) thin films has been well developed for RF applications with high and tunable permeability and moderate loss. A full investigation on the characteristics of the engineered substrate is presented in this paper. The loss and equivalent permeability generated by the Py patterns are characterized through a microstrip line model. Multiple factors of Py patterns are taken into consideration to define the performance of the engineered substrate, including filling density, thickness, dimensions, and locations. The analytical results give a detailed guideline for the design of engineered substrate.**

Keywords—Py patterns; engineered substrate; characterization; microstrip line

I. Introduction

Modern wireless communications and radar systems are miniature in size and required to operate at multiple-frequency bands to provide enhanced performances [1]. With the rapid deployment of 5G communication systems, multiband high-speed data-transfer capability and small scaling front ends are highly required.

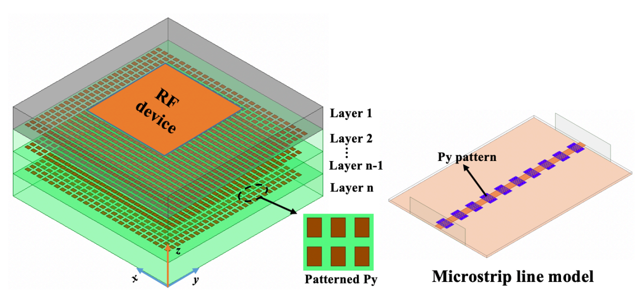
To support the continuing evolution, great efforts have been spent on developing tunable and miniaturized RF and microwave components, including mechanically tunable structures, electrically switched capacitor networks, magnetically tunable ferroelectric or ferromagnetic substrate, etc. All of these technologies can provide dynamic frequency behavior but may suffer from the issues of low tuning speed, complex structure or degraded performance [2]. To overcome these problems, electrically tunable engineered substrate enabled with ferromagnetic thin films has been developed to provide a flexible and common method for miniaturization and tunable frequency response [3]. Magneto-dielectric substrate implemented with multiple layers of Permalloy ($Ni_{80}Fe_{20}$, Py) thin films has high and continuously tunable permeability by applying DC current. Attractive properties of the engineered substrate have found a lot of prospective applications such as miniaturization of RF components, wide tunable operating frequencies, and increased antenna bandwidth [4]. However, magneto-dielectric substrate suffers from high resistive losses generated by the introduced eddy current on the surface of Py thin film. To overcome this and increase the ferromagnetic resonance (FMR) for RF and microwave applications, although strategies have been developed by patterning Py thin films with selective sizes and aspect ratios [5], it is still a challenge to implement an engineered substrate with specific characteristics (e.g., equivalent permeability, losses). In other words, the effects of the Py patterns on the entire engineered substrate should be fully investigated and analyzed.

In this paper, a microstrip line model is employed to characterize the effects of Py thin film patterns on the design of engineered substrate. The vertical location, thickness, filling density and dimensions of the Py patterns are studied. A design guideline is provided to determine the configuration of the engineered substrate with the required permeability and substrate loss.

II. Engineered Substrate Characterization

As shown in Fig. 1 (a), the well-developed engineered substrate consists of arbitrary RF substrates and multiple layers of patterned Py thin films [3]. Performances of RF devices designed on engineered substrate are dependent on the properties of the substrate. Therefore, it is critical to understand the effects of the Py patterns on the entire engineered substrate in terms of effective permeability and loss.

In order to reduce the calculation and computing time required for the simulation, a simple engineered substrate is implemented with a 0.5mm thick substrate (Roger RT/Duriod 5880: ε_r=2.2, μ_r=1.0, tanδ=0.0009) and one layer of Py patterns (Permalloy: ε_r=1.0, μ_r=1000, conductivity=1.2e^7 S/m). A 50Ω microstrip line, as depicted in Fig. 1 (b), is then designed on the engineered substrate to explore the effects generated by the Py



(a) (b)

Fig. 1. Illustration of (a) engineered substrate, and (b) Microstrip line designed on the engineered substrate.

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patterns, including effective permeability and loss. Fig. 2 (a) gives the HFSS simulated *S*-parameters of the microstrip line on regular substrate and Py enabled engineered substrate. By

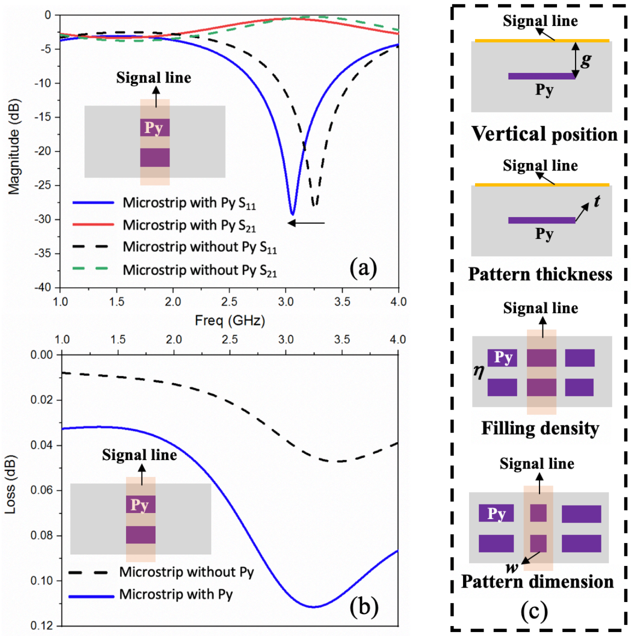

Fig.2. Performance comparison of microstrip line on substrate with or without Py patterns: (a) *S*-parameters, (b) Loss. (c) Factors considered for the engineered substrate modeling.

comparing the resonant frequency of the microstrip, it is obvious that the Py engineered substrate has higher effective permeability. In addition, the attenuation loss is given as

$$Loss = -10\log(\frac{|S_{11}|^2 + |S_{21}|^2}{1}) \quad (1)$$

Hence, the loss comparison as shown in Fig .2 (b) indicates that additional loss is introduced by the Py patterns in engineered substrate.

Based on the above characterization method, four factors illustrated in Fig. 2 (c) are considered to fully investigate the effects of the Py patterns for optimum properties of implemented engineered substrate. The location of Py patterns, the vertical distance (*g*) between the Py patterns and the signal line, is studied first. Various pattern thicknesses (*t*) have also been studied by increasing the pattern thickness while keeping the *g* constant. The third factor considered is the filling density of Py patterns, which is defined as

$$\eta = \frac{A_{Py}}{A_{Sub}} \quad (2)$$

where A_{Py} represents the area of Py patterns and A_{sub} denotes the surface area of the substrate. Finally, keeping the same filling density and changing the width (*w*) of Py patterns, equivalent permeability and losses of the engineered substrate are analyzed from the simulated results of microstrip line on substrate with Py patterns having different dimensions.

III. Results and Discussions

Due to the page limitation, detailed simulated results are not shown in this paper with summarized trend in Table I. When the Py patterns are close to the signal line, the permeability effect will increase but more loss will be introduced. A similar trend can also be found when increasing the thickness of Py patterns. In addition, higher filling density will generate larger permeability but worse signal transmission. When the filling density is fixed, the dimensions of the patterns beneath the signal line play an important role in the engineered substrate performance. In conclusion, the effective permeability of the engineered substrate can be increased by changing the listed factors, while the additional loss will be generated degrading the performance of the RF devices on the substrate.

TABLE I. Summary of the Py Patterns Effects for Different Factors

Performance	***Increased g***	***Increased t***	***Increased η***	***Increased w***
Permeability	↑	↑	↑	↑
Loss	↑	↑	↑	↑

IV. Conlcusion

This paper investigates the effects of Py patterns on the effective permeability and loss in the engineered substrate. Vertical location, thickness, filling density, and dimensions of Py patterns are taken into consideration and a preliminary relationship between the permeability and loss is concluded. Higher permeability can be achieved by making the Py patterns closer to the RF device, increasing thickness, filling density and the width of Py patterns. However, additional loss will be introduced to deteriorate the electromagnetic performance. This paper provides a detailed guideline for the design of the engineered substrate.

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