Thin Film Enabled Tunable Engineered Substrate for Reconfigurable RF and Microwave Applications

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Abstract— **This paper presents a methodology in the development of miniaturized and electrically tunable RF and Microwave passives with engineered substrate which has high and electrically tunable effective permeability. The perspective substrate is implemented with multiple layers of 100 nm thick Permalloy (Py) thin film patterns embedded on Silicon substrate, and each Py layer consists of an array of 15µm×40µm Py patterns with 5 µm gaps among them to suppress the magnetic loss. The effective permeability of the single layer and ten layers of Py enabled substrate is tunable by the static magnetic field produced from the applied DC current providing a tunability of 3.3% and 18.8%, respectively. Passives are developed on the proposed engineered substrate with a single layer embedded Py to demonstrate the efficacy of the engineered substrate on the design of arbitrary tunable components. Results show that the developed transmission line-based phase shifter provides continuous 90^{o} phase shift from 0.956 GHz to 1.01GHz, and the center frequency of the bandpass filter shifts from 2.42GHz to 2.56GHz continuously.**

Index Terms—**Engineered Substrate, Ferromagnetic Thin Film, Phase Shifter, Filter, Frequency Reconfigurable**

I. Introduction

Recent developments in wireless communications have resulted in the radio to support multi-mode and multiband high-speed data-capable system. The trend continues today with rapid deployment of 5G and beyond systems, driving new bands and modes of operation. To support multiple standards which has its own unique characteristics, constraints and specific challenges, frequency tunable and multifunctional circuits are explosively demanded in current and next generation communication systems, radars, sensor networks, and biomedical applications. Solutions to the evolution are driven by both the scaling of CMOS technology and smart integration in the front end, however, RF and microwave passives pose particular challenges to further scaling due to the physical limits. To support the continuing evolution, new enabling technologies must be introduced as the limits of improvements through packaging and hybrid integration are approached.

Great efforts have been spent on developing tunable and miniaturized RF and microwave components that incorporates multiple cellular modes and other functionalities with technologies such as switched capacitor networks, ferrielectric and ferromagnetic thin film, and Microelectromechanical systems (MEMS). These approaches all offer the ability to dynamically change the impedances within a component while introducing a minimum loss. Switched capacitors have been used to design filters, voltage converters and antenna load tuning network [1-3]. Low voltage operation with low cost standard technology can be achieved. Ferroelectric materials such as BST provide high and DC voltage controllable capacitance density and have been commonly used to control the frequency and/or phase response of electronically steerable phased array antennas, oscillators, and filters [4-6]. Another important class of tunable RF devices are RF MEMS which have been successfully applied in developing tunable filters, matching networks, antennas, and phase shifters [6-8]. However, Current adaptive RF technologies still have limitations providing arbitrary tunability in practical multiband applications: ferromagnetic materials are generally tuned with external magnetic field, which is often slow, bulky, and noisy [9, 10]; RF MEMS technologies confront reliability and complex integration issues. Tunable RF components with both ferromagnetic and ferroelectric thin films have also been directly studied [11, 12]. In general, the tunability of current technology is directly dependent on the specific design of individual components.

A novel unique methodology with more frequency agile capability and design flexibility is proposed in this paper to solve those issues from the perspective of smart material. An electrically tunable engineered substrate is proposed for the development of reconfigurable RF and microwave components with the current state-of-the-art arbitrary designs. The substrate is implemented with multilayer embedded ferromagnetic (e.g., Py) thin film patterns on arbitrary substrates. The proposed substrate is unique with both high and tunable permeability. This paper is organized as the following: section II provides implementation and tuning mechanism of engineered substrate, and section III provides the results of a phase shifter and bandpass filter developed on the proposed substrate.

II. Implementation of engineered Substrate

Ferromagnetic films have been explored for high-performance magnetic microwave devices. For example, Py ($Ni_{80}Fe_{20}$) which has high permeability value ranging from 200 to 9000 is a promising material for the construction of engineered substrate. Although ferromagnetic resonance (FMR) loss limits the application of Py in high frequency, the magnetic loss of Py could be suppressed and its FMR frequency can be increased using selectively Py patterns sizes and aspect ratios. The permeability of Py thin film is tunable by the applied external magnetic field, and it could also be adjusted directly using DC current [11, 12]. As shown in Fig. 1, a DC current can be applied through the metal DC bias lines which tune the magnetization distribution inside the Py thin film. The static magnetic field generated by DC current tilts the magnetization direction in the film away from its easy axis towards its hard axis, and thus the total inductance density and equivalent permeability of Py thin film is decreased consequently. The maximum Ampere's fields associated with the applied DC currents can be estimated with Ampere's law:

$$H_{DC} = \frac{I_{DC}}{2W} \quad (1)$$

Where I_{DC} is the applied DC current and W is the width of the metal bias lines. And the relative permeability of magnetic sphere can be expressed as the function of the magnetic field.

$$\mu_r = \frac{4\pi M_s}{H_{net}} + 1 \quad (2)$$

Where H_{net} refers to the net magnetic field of the ferromagnetic film. It shows that the effective permeability of the ferromagnetic film is inversely proportional to the effective magnetic anisotropy field.

A 3D view of the proposed magneto-dielectric substrate enabled with patterned Py thin film is shown in Fig. 2. 100 nm thick Py thin film is deposited on silicon substrate using DC magnetron sputtering method in air atmosphere with controlled N_2 admixture. The Py thin film is patterned into an array of 15um×40um stripes with a 5um gap among them. An array of 10nm thick gold lines are deposited and patterned under Py patterns providing DC bias path. Since the gold line arrays have very high conductivity, the extra loss introduced by the gold line can be limited to a tolerable range. Fig. 3 shows the image of the implemented engineered substrate with a single layer of Py patterns.

III. Tunability Demonstration

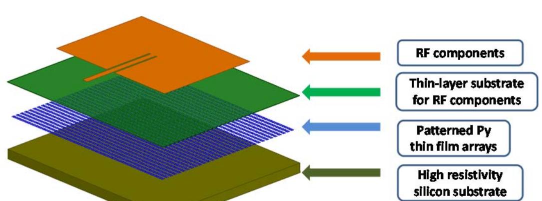

Fig. 2 3D view of engineered substrate with embedded ferromagnetic thin film layer

To demonstrate the efficacy of the proposed engineered substrate on the development of electrically tunable RF and microwave passives, a transmission line-based phase shifter and a bandpass filter are designed. The components are fabricated on 100 μm thick liquid crystal polymer (LCP0 substrate first and then bonded with the engineered substrate embedded with a single layer of Py thin film patterns. The separated fabrication of the substrate and RF components provides a flexible and cost-effective method to develop tunable components with the same engineered substrate by reducing the time-consuming fabrication process of patterning Py.

A. Tunable Phase Shifter

A tunable transmission line-based phase shifter was fabricated on LCP substrate and implemented with the engineered substrate as shown in Fig.4. The characteristic impedance of the lossless transmission line is equal to the square root ratio of inductance to capacitance per unit length $Z = \sqrt{L/C}$. The inductance per unit length of the transmission line can be adjusted by

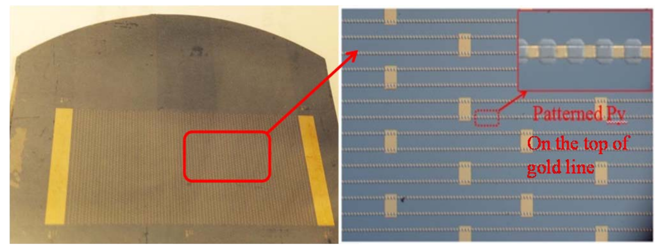

Fig. 3 Implemented engineered smart substrate with zoom-in view of patterned Py film and DC bias line arrays

tuning the equivalent permeability of the overall substrate with applying DC current. Without the presence of the patterned Py film, the transmission line presents a phase shift of 90º at 1.09 GHz. Applying the DC current from 0mA to 400mA, the developed transmission line provides constant 90º phase shift from 0.956 GHz to 1.01GHz as shown in Fig. 4. Selecting the right tuning DC current, a 90º phase shift can be achieved at an arbi-

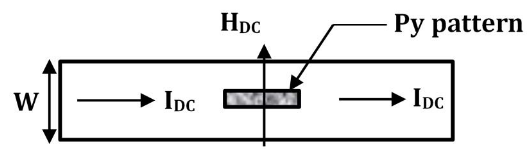

Fig. 1 Illustration of DC current tuning mechanism of Py patterns, H_{DC} stands for the Ampere's field produced by the DC current I_{DC}

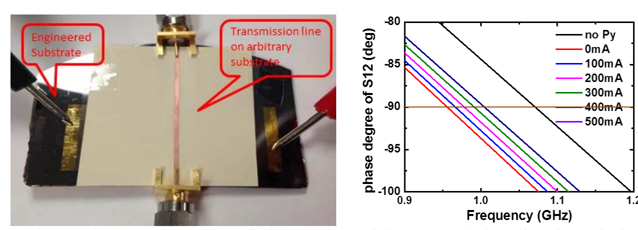

Fig. 4 Photo and measured phase of tunable transmission line-based phase shifter on engineered substrate

trary desired frequency. It shows that the electrically tunable engineered substrate provides a continuous tuning capability.

B. Tunable Bandpass Filter

To further demonstrate the tuning efficacy of the engineered substrate, an SRR type bandpass filter is designed with a dimension of 12.8mm×8mm as shown in Fig. 5. Two feeding lines are extended to the edge of the substrate for the convenience of measurement. The center frequency of the bandpass filter is moved to a higher frequency with the larger DC current applied. Applying DC current from 0mA to 800mA through the gold bias lines, the center frequency of the band-pass filter can shift from 2.42GHz to 2.56GHz continuously with an insertion

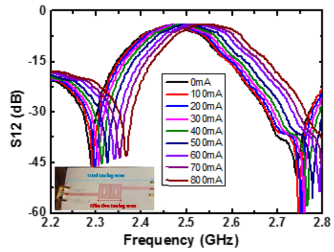

Fig. 5 Photo and measured S12 of bandpass filter on engineered substrate

loss of less than 1.5 dB. It showed that when the DC current is less than 400mA, the frequency tunable range for each 100mA increase is around 7MHz. When the DC current is more than 400mA, the tuned center frequency shift of 20MHz can be achieved with every increment of 100mA applied DC current.

C. Tuning Discussions

In this paper, for a simple and quick feasibility demonstration of the proposed methodology on the development of electrically reconfigurable components, engineered substrate is developed with only a single layer of Py thin film. The tunability of the implemented phase shifter and filter is 5.6% and 5.8%, respectively. Larger tunability could be achieved on substrate with more embedded layers of Py thin film. Table I summarizes the comparison of equivalent permeability under different DC conditions for substrate with single and 10 layers Py films. For example, the tunability of the implemented phase shifter and filter on the substrate having 10 layers Py patterns could be increase to about 20%.

IV. Conclusion

An engineered substrate enabled with ferromagnetic thin film is proposed to develop electrically tunable RF and microwave passives. Implementation and tunability mechanism of the proposed engineered substrate are discussed and studied. The design efficacy of RF and microwave passives with the proposed engineered substrate has been demonstrated with the realization of a frequency continuously tunable phase shifter and a bandpass filter. Further improvement of the tunability could be achieved by optimum implementation of engineered substrate.

TABLE I
Comparison of Equivalent Permeability Tunability

DC CURRENT (mA)	μ_r	
	Single Layer Enabled Substrate	Ten Layer Enabled Substrate
0	1.140	2.398
100	1.134	2.338
200	1.130	2.298
300	1.123	2.228
400	1.109	2.088
500	1.102	2.018

Taken together, the envisioned engineered smart substrate provides a comprehensive solution and a major breakthrough developing arbitrary multi-band integrated RF and microwave passive components for various applications.

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