Electrically tunable miniaturized band-stop frequency selective surface on engineered substrate with embedded permalloy patterns

Cite as: AIP Advances 9, 125145 (2019); https://doi.org/10.1063/1.5129035
Submitted: 24 September 2019 . Accepted: 09 November 2019 . Published Online: 27 December 2019

Jinqun Ge <sup>1</sup>, and Guoan Wang <sup>1</sup>

<sup>1</sup>openaccess

View Online  Export Citation  CrossMark
Electrically tunable miniaturized band-stop frequency selective surface on engineered substrate with embedded permalloy patterns

Cite as: AIP Advances 9, 125145 (2019); doi: 10.1063/1.5129035
Presented: 8 November 2019 • Submitted: 24 September 2019 • Accepted: 9 November 2019 • Published Online: 27 December 2019

Jinqun Ge and Guoan Wang

AFFILIATIONS
Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina 29208, USA

Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.
gwang@cec.sc.edu

ABSTRACT
This paper presents a miniaturized and electrically tunable band-stop frequency selective surface (FSS) with magneto-dielectric engineered substrate which has high and electrically tunable effective permeability. The perspective magneto-dielectric substrate is implemented with multiple layers of 100 nm thick patterned Permalloy (Py) thin film embedded in Roger RT/Duriod 5880 substrate, and each Py thin film layer consists of an array of 15μm×20μm Py patterns with 10 μm gaps among them to suppress the magnetic loss. The tunability of effective permeability for the proposed substrate is achieved by the static magnetic field produced from the applied DC current through the patterned gold bias lines beneath Py patterns. The engineered substrate has been implemented and studied, results show that the substrate embedded with a single layer of patterned Py has an equivalent permeability of 1.14 with tunability of 3.3%, and the substrate embedded with ten layers of patterned Py has an increased equivalent permeability of 2.398 and tunability of 15.8%. A magnetic FSS is designed on the implemented engineered substrate to demonstrate the efficacy of miniaturization and tunability. Compared to non-magnetic FSS on normal dielectric substrate, the size of the designed FSS has been reduced by 16.02%, and the operating frequency of the proposed FSS is continuously tunable from 2.450GHz to 2.672GHz with DC current.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5129035

I. INTRODUCTION

Frequency selective surfaces (FSSs) which are usually two-dimensional (2-D) infinite arrays, acting as spatial filters for the incident electromagnetic waves, have been widely investigated over the past decades. In recent years, tunable FSSs attracted great interest wide applications such as tunable filters in multiband reflector antennas, tunable radar absorbers, and radomes. Many approaches have been utilized to generate a dynamic frequency behavior: mechanically tunable surface with a changing shape, magnetically tunable surface with biasing magnetic field, and electrically tunable surface with a tuning voltage. However, the mechanically and magnetically tunable FSSs suffer from several disadvantages, i.e., low tuning speed, high loss, and complicated design, it is critical to study electrically tunable FSSs due to their advantages of small size, high tuning speed, and low cost.

In addition, with high and tunable effective permeability, magneto-dielectric materials provide more flexibility in the design of high-performance reconfigurable RF components. Although many efforts have been spent to develop various magneto-dielectric substrates, such as applying artificial magnetic conductor layers, building metamaterials with embedded resonant circuits, etc., these approaches still suffer from the issue of either high magnetic loss or bulk substrate. Magneto-dielectric substrate implemented with a single layer of Permalloy (Ni₈₀Fe₂₀) thin film has been studied, which has an increased and tunable permeability with DC current, and the ferromagnetic resonance (FMR) frequency of Py is improved by patterning ferromagnetic film with selectively aspect ratio and composition of magneto-dielectric materials.

In this paper, a high performance electrically tunable and miniaturized FSS is developed on a magneto-dielectric engineered substrate implemented with multiple layers of patterned Py thin
film embedded on a Roger RT/Duriod 5880 substrate. The principle of square loop FSS and the design procedure of the proposed tunable magnetic FSS on engineered substrate are first discussed in Section II. In Section III, the proposed engineered substrate is investigated and experimental validated for its electrical tunability, and a miniaturized frequency tunable FSS is designed and demonstrated.

II. DESIGN PRINCIPLE AND IMPLEMENTATION

Frequency selective surface is formed with multiple unit cells. As shown in Fig. 1(a), a square copper loop type unit cell is designed with a period of \( p \), a width of \( w \), and an inner side length of \( s \). The copper loop has a thickness of 17\( \mu m \) and is fabricated on a Roger RT/Duriod 5880 substrate (\( \varepsilon_r = 2.2, \mu_r = 1.0, \tan \delta = 0.0009 \)) with a thickness of 2mm. The square loop forms a first-order band-stop filter, and the equivalent circuit of this FSS is shown in the insert of Fig. 1(a) which is a series LC network parallel connected with a transmission line has a characteristic impedance of \( Z_0 \approx 377 \Omega \) (the intrinsic impedance of free space). \(^\text{11}\) From the equivalent circuit model, the operating frequency of the square loop FSS can be approximately calculated by:

\[
f_0 = \frac{1}{2\pi \sqrt{LC}} \tag{1}
\]

where the inductance and capacitance are directly dependent on the permeability (\( \mu_r \)) and permittivity (\( \varepsilon_r \)) of the substrate, respectively. For example, as shown in Fig. 1(b), the operating frequency of the designed FSS is changed from 5.75 GHz to 5 GHz when the effective permeability of the substrate changes from 1 to 2 which increases the inductance value.

Designing FSS with a larger permittivity substrate generates a higher capacitance density, unit cell of FSS is required to be miniaturized to maintain the same resonant frequency. However, because of the strong capacitive coupling between adjacent unit cells, the FSS’s performance is considerably degraded. To overcome this problem, magneto-dielectric substrate is designed in this paper to adjust both \( \mu_r \) and \( \varepsilon_r \) instead of only \( \varepsilon_r \) with traditional dielectric materials. In this way, the same miniaturization factor (\( n = \sqrt{\mu_r \varepsilon_r} \)) can be achieved by choosing moderate values of \( \mu_r \) and \( \varepsilon_r \), while the strong coupling between the adjacent unit cells is reduced. Therefore, compared to dielectric-only frequency selective surfaces, utilizing magneto-dielectric material in a band-stop FSS design can easily achieve further miniaturization without deteriorating its performance.

The proposed miniaturized and tunable magnetic FSS is fabricated on the engineered substrate consisting of Roger RT/Duriod 5880 embedded with ten layers of patterned Permalloy (Py) thin films, as shown in Fig. 2(a)–2(c). The total thickness of the engineered substrate is 60\( \mu m \), and the thickness of a single Py thin film is chosen as 100 nm, which is less than the skin depth at the working frequency to minimize the loss. The relative permeability of Py is given as:

\[
\mu_r = \frac{4\pi M_s}{H_k + H_{DC}} + 1 \tag{2}
\]

where \( M_s \) and \( H_k \) represent the saturation magnetization and the internal induced magnetic field of Py film, respectively, and \( H_{DC} \) refers to the DC magnetic field generated from the applied DC current as shown in Fig. 2(d). Due to its high permeability, the eddy current is introduced on the surface of Py, resulting in resistive losses and lower effective permeability. To overcome this, the Py thin film is patterned in a dimension of 15\( \mu m \times 20 \mu m \) with a 10\( \mu m \) gap among patterns. The ten layers of Py thin films are placed in the dielectric at the same spacing, providing an equivalent permeability of 2.398 for the substrate. As depicted in Fig. 2(c) and 2(d), gold lines of 10nm thick and 15\( \mu m \) wide are deposited beneath the Py patterns to apply DC current for tuning the characteristic of the Py. The extra loss introduced by the gold lines is limited to a tolerable range due to their high conductivity and small dimension. As shown in Fig. 2(d), the static magnetic field generated by the applied DC current tilts the magnetization direction in the Py pattern away from its
easy axis towards the hard axis, which changing the magnetization distribution, enabling the decrease of equivalent permeability consequently. The maximum Ampere’s field associated with the applied DC currents is estimated with Ampere’s law:

$$H_{DC} = \frac{I_{DC}}{2W_g}$$  \hspace{1cm} (3)

where $I_{DC}$ is the applied DC current and $W_g$ is the width of the gold bias line. In addition, the Joule heating effect from the DC current also changes the permeability of the Py thin films, which makes the electrically tunable method more efficient.13 The feasibility verification of the proposed miniaturized and electrically tunable FSS is presented in Section III.

III. RESULTS AND DISCUSSIONS

To characterize the frequency tunability performance of the proposed engineered substrate, a patch antenna is first measured on an engineered substrate with a single layer embedded patterned Py thin film. Fig. 3(a) shows an optical photo of the fabricated engineered substrate. Py film of 100 nm thick is deposited with DC Magnetron sputtering technology and patterned with a dimension of 15μm×20μm. A simple transmission-line-fed patch antenna designed on a 100μm thick LCP substrate was then bonded to the engineered substrate, as shown in the insert of Fig. 3(b). The resonant frequency of the patch antenna can be described...
as \( f_0 = \frac{0.5L}{\sqrt{\mu_r \varepsilon_r}} \), where \( L \) is the length of the antenna. The measurement is done with Rhode & Schwarz ZVA 67 Network Analyzer. It is noted that the resonant frequency in Fig. 4(b) shifts from 2.46 GHz to 2.498 GHz when DC current is applied from 0mA to 500mA through the gold bias line, which provides a variable equivalent permeability of the Py film according to equation (3).

Table 1 summarizes the result comparison of resonant frequency and equivalent permeability of different substrates under various bias conditions. Results show that the engineered substrate with a single layer of Py film increases its equivalent permeability for 14%, and it is continuously tunable from 1.140 to 1.102. The equivalent permeability of the engineered substrate embedded with ten layers of Py thin films is tunable from 2.398 to 2.018, showing a 139.8% increase compared to regular dielectric substrates (\( \mu_r =1 \)). Higher equivalent permeability can be achieved by employing more layers of Py thin films or increasing the thickness of the individual Py thin films.

To validate the efficacy of designing electrically tunable miniaturized FSS with the proposed substrate, a regular FSS with the unit cell size of 0.285\( \lambda_0 \times 0.285\lambda_0 \) is implemented on a Roger RT/Duriod 5880 substrate embedded with ten-layer of 100 nm Py thin films, where \( \lambda_0 \) is the free space wavelength at the operating frequency (2.45GHz). It achieves a 16.02% size reduction compared to the FSS on regular substrate which has a unit cell size of 0.311 \( \lambda_0 \times 0.311\lambda_0 \). The performances of FSSs are compared and the results are shown in Fig. 4(a), it is shown that the proposed FSS on engineered substrate has significantly reduced size without deteriorating the performance. When DC current is applied through the gold bias line in the engineered substrate, the working frequency of the designed FSS shifts from 2.45 GHz to 2.672 GHz when DC current is increased from 0 mA to 500 mA, which fully demonstrates the design feasibility of the proposed miniaturized and electrically tunable FSS on engineered substrate.

**TABLE I. Effects of the engineered substrate to the equivalent substrate.**

| DC Current (mA) | Resonant Frequency (GHz) | Equivalent permeability (1 layer) | Estimated equivalent permeability (10 layers) |
|-----------------|--------------------------|----------------------------------|-----------------------------------------------|
| No Py           | 2.52                     | 1                                | 1                                             |
| 0mA             | 2.455                    | 1.140                            | 2.398                                         |
| 100mA           | 2.463                    | 1.134                            | 2.338                                         |
| 200mA           | 2.471                    | 1.130                            | 2.298                                         |
| 300mA           | 2.481                    | 1.123                            | 2.228                                         |
| 400mA           | 2.490                    | 1.109                            | 2.088                                         |
| 500mA           | 2.498                    | 1.102                            | 2.018                                         |

IV. CONCLUSION

A novel miniaturized and electrically tunable FSS on a Py thin film based engineered substrate is first developed and presented in this paper. The engineered substrate embedded with ten-layer patterned Py films can achieve a maximum equivalent permeability of 2.398, resulting in a 16.02% size reduction of the designed FSS. In addition, the center frequency of the proposed FSS can be continuously tuned from 2.45 GHz to 2.672 GHz by applying different DC current. Further size reduction and tunability range can be achieved by implementing engineered substrate with more or thicker layers of Py thin films. This work provides a concept of designing electrically tunable and miniaturized FSS with magnetic films enabled substrate. More transmission zeros can be introduced by the design optimization of FSS cell structure for sharp cut-off frequency response, which makes the frequency tunability more significant in practical applications.

ACKNOWLEDGMENTS

This work was support by National Science Foundation (NSF) under Award No. 19108563 and Navy Surface Warfare Center...
under Award No. 12738473 N001741910015. The authors also thank ANSYS for the software support of HFSS.

REFERENCES

1 T. K. Wu, Frequency Selective Surfaces and Grid Arrays (Wiley, New York, NY, USA, 1995).
2 B. A. Munk, Frequency Selective Surfaces: Theory and Design (John Wiley & Sons, Inc., New York, 2000).
3 L. Boccia, I. Russo, G. Amendola, and G. Di Massa, “Tunable frequency-selective surfaces for beam-steering applications,” Electron. Lett. 45(24), 1213–1214 (2009).
4 S. N. Azemi, K. Ghorbani, and W. S. T. Rowe, “A reconfigurable FSS using a spring resonator element,” IEEE Antenna Wireless Propag. Lett. 12, 781–784 (2013).
5 J. M. Zendejas, J. P. Gianvittorio, Y. Rahmat-Samii et al., “Magnetic MEMS reconfigurable frequency-selective surfaces,” J. Microelectromech. S. 15(3), 613–623 (2006).
6 M. Safari, C. Shafai, and L. Shafai, “X-band tunable frequency selective surface using MEMS capacitive loads,” IEEE Trans. Antennas Propag. 63(3), 1014–1021 (2014).
7 Y. Peng, B. M. Farid Rahman, X. Wang et al., “Performance enhanced miniaturized and electrically tunable patch antenna with patterned permalloy based magneto-dielectric substrate,” J. Appl. Phys. 115(17), 17AS05 (2014).
8 A. P. Ferenidis, G. Goussetis, S. Wang et al., “Artificial magnetic conductor surfaces and their application to low-profile high-gain planar antennas,” IEEE Trans. Antennas Propag. 53(1), 209–215 (2005).
9 B. M. F. Rahman, R. Divan, H. Zhang et al., “High performance tunable slow wave elements enabled with nano-patterned permalloy thin film for compact radio frequency applications,” J. Appl. Phys. 115(17), 17AS08 (2014).
10 Y. Peng, B. M. F. Rahman, T. Wang et al., “Engineered smart substrate with embedded patterned permalloy thin film for radio frequency applications,” J. Appl. Phys. 117(17), 17B709 (2015).
11 Y. Hsu, R. Fontana, M. Williams et al., “High frequency high field permeability of patterned Ni0.8Fe0.2 and Ni0.45Fe0.55 thin films,” J. Appl. Phys. 89(11), 6808–6810 (2001).
12 A. K. Rashid, B. Li, and Z. Shen, “An overview of three-dimensional frequency-selective structures,” IEEE Antennas Propag. Mag. 56(3), 43–67 (2014).
13 B. M. F. Rahman, R. Divan, L. Stan et al., “Tunable transmission line with nanopatterned thin films for smart RF applications,” IEEE Trans. Mag. 50(11), 1–4 (2014).