Performance Enhancement of Circularly Polarized Microstrip Antenna Using Thin Slot and Magnetic Material

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***Abstract*—The performance enhancement of a circularly polarized microstrip antenna is investigated by using thin slot and magnetic material. Two different microstrip antennas with a single thin slot and a magnetic material, respectively, are employed to investigate their characteristic performances, in particular, axial ratio (AR) and impedance bandwidth. A rectangular thin slot with the size of 7.2 mm×1 mm is arranged diagonally over the antenna patch, while a magnetic material with the size of 3 mm×3 mm×1 mm is embedded inside the dielectric substrate of the antenna host. The magnetic material utilized for investigation is Yttrium Iron Garnet (YIG) in the demagnetized state. Characteristic performances of the proposed microstrip antenna are then compared with the ones of conventional microstrip antenna. The characterization results show that the microstrip antenna with thin slot and magnetic material can improve –10 dB impedance bandwidth for more than 78% and 44%, respectively, whilst 3 dB AR bandwidth enhances up to 12% and 160%, respectively. In addition, the center frequency of both antennas that are shifted to the lower frequency region shows the feasibility in frequency tuning and miniaturization of the microstrip antenna.**

***Index Terms*—circular polarization; magnetic material; microstrip antenna; thin slot; Yttrium Iron Garnet (YIG).**

I. Introduction

Planar printed antenna such as microstrip antenna has been used over the years due to its low-profile and compact structures. Unlike the most conventional antenna, for instance wire or horn antenna, this type of antenna is possible to be integrated to microwave integrated circuits with single-board solution. However, owing to its thin thickness, usually less than $0.02\lambda_o$, the microstrip antenna suffers from narrow impedance bandwidth and generates mostly linear polarization by its nature [1]. Meanwhile, in particular application such as wireless communications where undesirable signal degradation affected by multipath fading was unneglectable, utilizing radiation characteristics of microstrip antenna to produce circular polarization will be beneficial to reduce the effect as well as Faraday rotation and to minimize unwanted polarization loss due to mismatch polarization of transmitting and receiving antennas.

In microstrip antenna, wide impedance bandwidth can be achieved by increasing the thickness of the antenna substrate at the expense of its compact size. Wideband antenna could also be realized by cutting the edge of radiating patch fed by a coplanar waveguide [2]. Furthermore, bandwidth characteristic of log-periodic fractal Koch printed antenna that has similar structure to microstrip antenna is investigated using series iteration showing that the antenna bandwidth depends on the number of iterations [3]. As this antenna is a balanced antenna type, then an additional element, i.e., balance-unbalance (balun) circuit, is required for excitation and impedance matching. In addition, due to its simple configuration, a slot over the radiating element is also widely implemented in broadening –10dB impedance bandwidth as it reduces Ohmic losses and decreases quality factor of the antenna [4]–[6]. On top of that, by utilizing the thin slot, orthogonal surface current can be provoked with a result in producing circular polarization and enhancing 3dB axial ratio bandwidth [7]–[10]. Whilst, in [11], two linear orthogonal components with the same amplitude and phase difference were generated by exciting radiating patch elements at the opposite sides differentially. However, its feeding line was complex and high Ohmic losses leading to the radiation performance degradation.

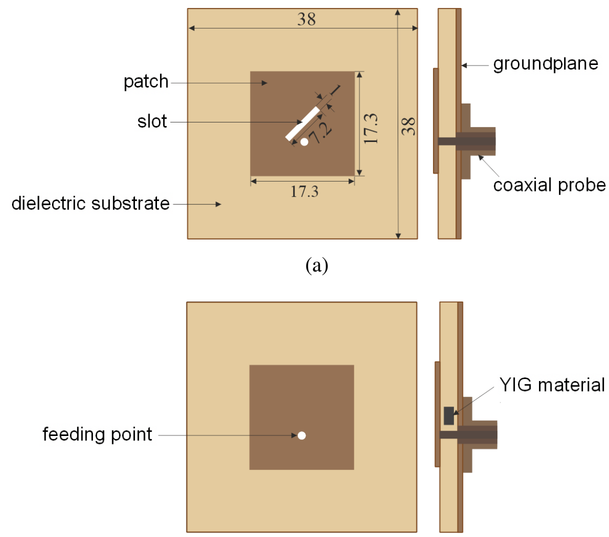
Another method is performed by loading the antenna with magnetic material or using artificial magneto-dielectric to adjust material properties, such as relative permeability and relative permittivity, thereby enhancing the impedance bandwidth [12]–[13]. However, its performance depends on the number of unit cell of the etched structures in the groundplane where its size cannot be adjusted over the patch length [13]. In [14], magnetic material is embedded inside a square defected ground structure to enhance radiation characteristics of microstrip antenna. It is shown that the polarization characteristic could be enhanced up to 90% through experimental approach with the absence of external magnetic bias, but the fractional impedance bandwidth remains the same. Furthermore, the use of self-biased magnetic thin film has also been investigated [15]. Despite the polarization improved at its center frequency, the antenna still suffer from low 3dB axial ratio bandwidth. Meanwhile, the magnetic material under magnetically biased state could also improve the axial ratio value by increasing magnetization using an external magnetic field [16]. Nevertheless, fabrication processes sometimes become more complex as fully magnetic material is used as a host substrate.

In this paper, circularly polarized microstrip antenna with enhanced performance is designed and characterized through simulation. The proposed microstrip antennas are configured on a single layer of FR4 dielectric substrate and excited directly using coaxial feeding method to avoid spurious emission. The microstrip antennas are intended to work at the center frequency of 4 GHz. Moreover, two different configurations using a single thin slot and a magnetic material using Yttrium Iron Garnet (YIG) are implemented to attain circular polarization and expected to improve impedance bandwidth as well. It is already-known that YIG material is commonly employed as magnetostatic devices due to its high performance characteristic for high frequency applications [17]. In addition, to investigate its effect to the antenna performances, parametric study is carried out by varying physical parameters of YIG material. Afterward, the performance of the proposed antennas are plotted together in comparison with a conventional microstrip antenna to figure out its improvement.

II. Overview of Microstrip Antenna Design

Two proposed configurations of microstrip antenna are depicted in Fig. 1. The microstrip antennas are modified by incorporating a single thin slot upon its radiating patch and by embedding a magnetic material in the antenna substrate. These are to investigate the effect of each attempt to the antenna performance, in particular, the impedance bandwidth and the axial ratio bandwidth which refers to circular polarization capability. Both microstrip antennas are designed using a single layer of FR4 epoxy dielectric substrate with the thickness (t) of 1.6 mm, while the relative permittivity (ϵ_r) and the tangent loss (tan-δ) are 4.2 and 0.02, respectively. To achieve the resonant frequency of 4 GHz, the radiating patch has the dimension of 17.3 mm×17.3 mm, whereas the antenna substrate is 38 mm×38 mm.

As illustrated in Fig. 1, the radiating patch is excited using a coaxial probe feeding method where the inner conductor of coaxial connector is directly connected to the patch while the outer conductor is coupled to the groundplane. This feeding method is chosen due to its simply configuration, easy to fabricate, and has low spurious radiation. As a result, it is expected that the feeding structure has a slight effect to the antenna performance. Moreover, matching impedance of coaxial-fed antenna is controlled by feeding point position. The feeding point is usually placed at one-third of the patch length (L) from the patch edge in order the antenna works at the dominant resonance mode. In the design, the antenna



(a)

(b)

Fig. 1. Two proposed configurations of microstrip antenna (dimensions are in mm unit), (a) with thin slot, (b) with YIG material.

feeding point is positioned 3 mm from the center point of radiating patch. It should be noted that by using this feeding method, the antenna will also be operable at the higher order resonance mode.

Moreover, the radiating patch of microstrip antenna for the first configuration is incorporated by a single rectangular thin slot that is positioned symmetrically over the patch, as shown in Fig. 1(a). With the presence of thin slot, the patch area is diminished and reduced Ohmic loss from microstrip conductor which then leads the decrease of quality factor and conversely increase the antenna bandwidth. In addition, the thin slot is arranged diagonally over the patch to force the electric field to be distributed in the direction of the thin slot and produce two orthogonal linearly polarized electric fields with the same amplitude and a phase difference of 90^o. The length (l_s) and width (w_s) of the thin slot are approximated using (1) and (2) [18], respectively. Parametric study is then carried out regarding the dimension of thin slot to attain the desirable antenna performance. Here, the final dimension of thin slot is 7.2 mm (length) × 1 mm (width).

$$l_s = \frac{L}{2.72} \tag{1}$$

$$w_s = \frac{l_s}{10} = \frac{L}{27.2} \tag{2}$$

Furthermore, for the second configuration, instead of utilizing high profile structure material, a small size of magnetic material with a chemical structure of $Y_3Fe_5O_{12}$, known as Yttrium Iron Garnet (YIG), is embedded in the antenna substrate and beneath the radiating patch without intersecting the inner conductor of connector, as depicted in Fig. 1(b). The impedance bandwidth (BW) of microstrip antenna embedded using magnetic material can be approximately determined using (3) [19], where ϵ and μ are the permittivity and permeability of the material, respectively. It is noted that the presence of magnetic material causes magnetic energy stored on the antenna substrate increases to compensate the total electrical energy under the patch, thereby decreasing the quality factor and increasing the antenna bandwidth without increasing the antenna aperture.

$$BW = \frac{96\sqrt{\frac{\mu}{\epsilon}}(\frac{t}{\lambda_o})}{\sqrt{2}(4+17\sqrt{\mu\epsilon})} \tag{3}$$

In this work, the effect of YIG material to the antenna performance is examined in a demagnetized state with the absence of the external magnetic field. The properties of YIG material are 1750 Gauss for saturation magnetization and 5172 kg/m^3 for mass density, while the dimension is 3 mm×3 mm×1 mm (length × width × height). Simulated field distributions of microstrip antenna with and without YIG material are depicted in Fig. 2. It can be seen from Fig. 2(a) that the orientation of electric field distribution changes with the presence of magnetic material in the antenna substrate, whereby this also applies for the magnetic field distribution as plotted in Fig. 2(b). It shows that the highest magnetic field distribution on the surface of microstrip antenna is no longer linearly distributed at the center of radiating patch as the presence of magnetic material, but also distributed at the edge of radiating patch. The interaction between the electromagnetic field of the microstrip antenna and magnetic field induced by the YIG material is expected affecting the electric field to have phase difference with the same amplitude and evokes circular polarization. In addition, as a comparative study, the size of YIG material is varied with several different sizes (length × width). As plotted in Fig. 3, the proposed microstrip antenna tends to produce two adjacent resonant frequencies with frequency tunability along the increase of YIG material size.

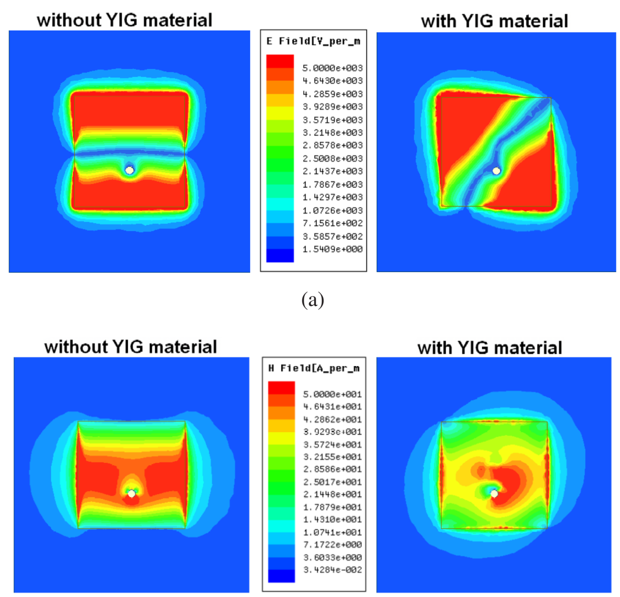


Fig. 2. Simulated field distribution of microstrip antenna with and without YIG material, (a) electric field, (b) magnetic field.

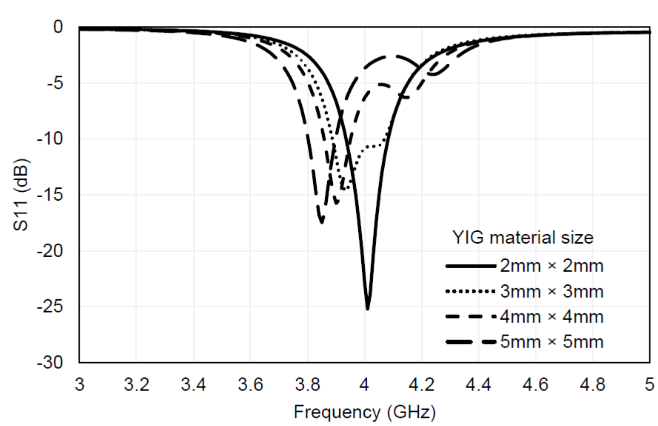


Fig. 3. Effect of YIG material size on simulated reflection coefficient of microstrip antenna.

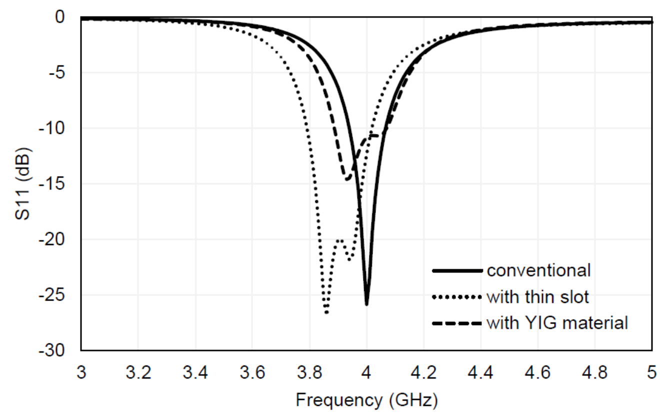
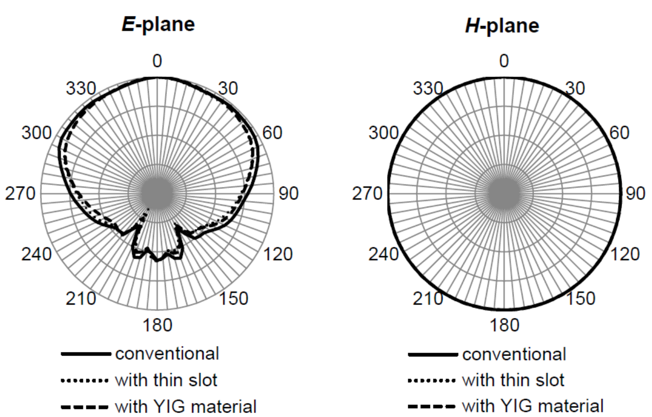


Fig. 4. Comparison of simulated reflection coefficient.

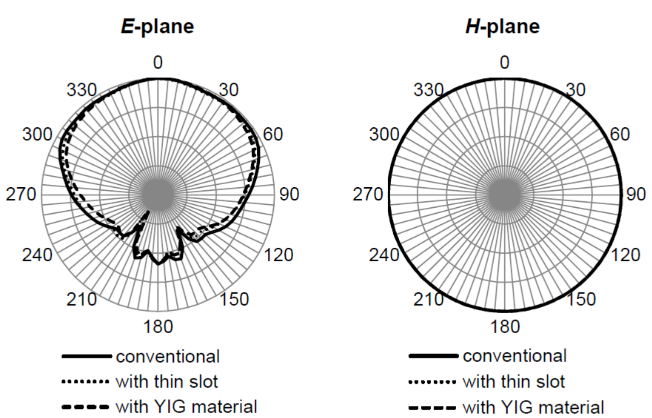
III. Characterization and Discussion

In this section, the microstrip antennas with a single thin slot and YIG material are characterized through simulation. Each corresponding results from the conventional microstrip antenna with the same manner is plotted together to demonstrate the improvement. As depicted in Fig. 4, the resonant frequency of microstrip antenna with thin slot shifts to the lower frequency region, from 4 GHz to 3.86 GHz, compared to the conventional ones due to alleviation of radiating patch area. Meanwhile, as a YIG material is embedded in the antenna substrate, then the relative permeability of microstrip antenna changes and leads to the shift of resonant frequency, that is from 4 GHz to 3.94 GHz, for microstrip antenna with YIG material. This results shows the possibility of resonant frequency tuning and miniaturization as well. Although there was a shift in a resonant frequency, both antennas can still operate at the desired resonant frequency of 4 GHz with acceptable reflection coefficient (S_{11}) below –10 dB.

Additionally, besides using a thin slot as a common method to improve impedance bandwidth, YIG material which is embedded in the antenna substrate beneath the radiating patch could also enhance the impedance bandwidth of microstrip antenna. The impedance bandwidth of microstrip antenna using a thin slot and YIG material is 227.5 MHz and 183.6 MHz where its improvement up to 78% and 44%, respectively, compared to the conventional one. Moreover, microstrip antennas with thin slot and YIG material have a slight effect to the radiation pattern, both in *E*- and *H*-planes at the resonant frequency of 3.94 GHz and 4 GHz as plotted in Fig. 5. Although the resonant frequency shifts to the lower frequency region due to the presence of thin slot and YIG material, the radiation pattern at the lower frequency remains the same with the conventional one that resonates at the center frequency of 4 GHz. In spite of the occurrence of backlobe in *E*-plane, adequate front-to-back ratio (FTBR) of the microstrip antenna using a thin slot and YIG material is still maintained at the value of 16.1 dB and 19.3 dB, respectively, at the resonant frequency of 4 GHz. By embedding YIG material, the microstrip antenna has better FTBR compared to the conventional one that has FTBR of 17.1 dB. It denotes that proposed microstrip antennas tend to have directionally radiation patterns similar to the conventional one. As plotted in Fig. 6, the simulated gain remains the same with the peak gain of 4.6 dB, 4.6 dB, and 4.5 dB for conventional microstrip antenna, with thin slot, and with YIG material, respectively.



(a)



(b)

Fig. 5. Comparison of simulated radiation patterns, (a) at frequency of 3.94 GHz, (b) at frequency of 4 GHz.

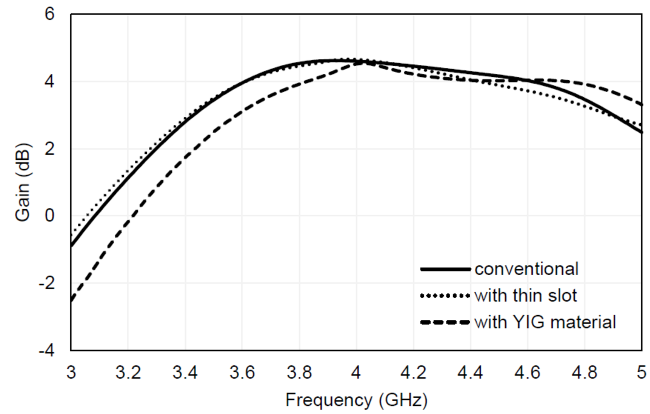
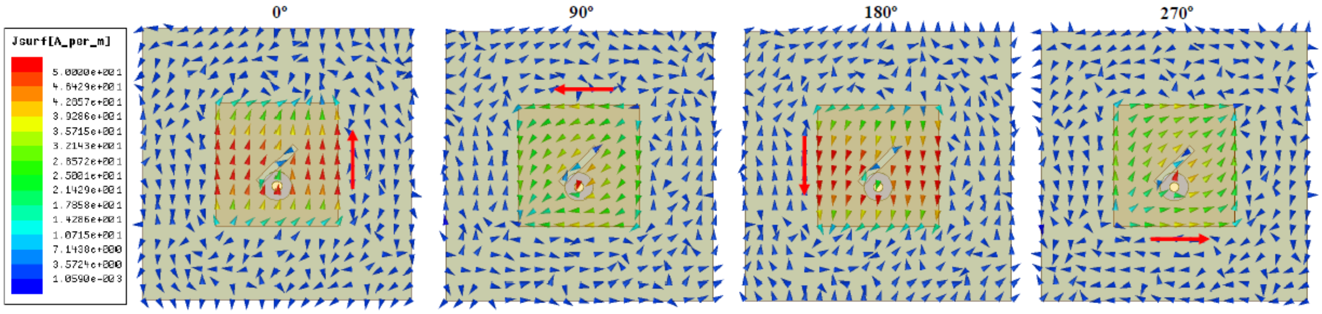


Fig. 6. Comparison of simulated gains.

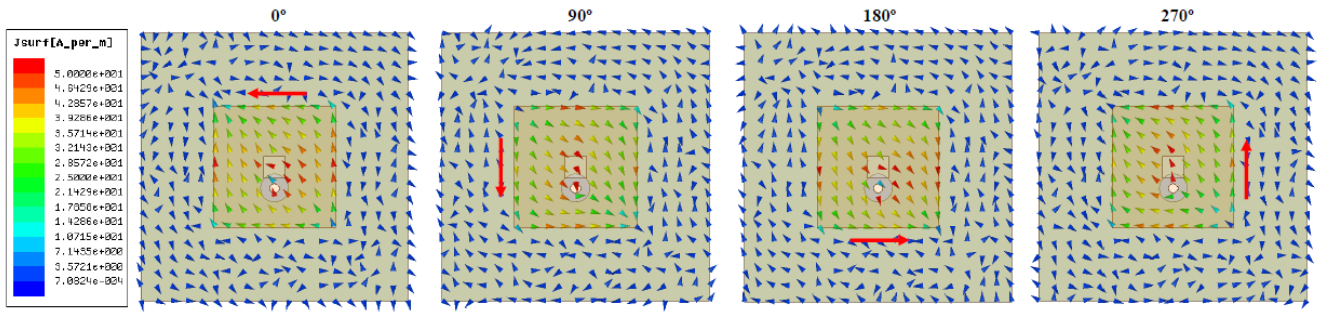
Furthermore, polarization capability of microstrip antenna is characterized by the current distribution and the axial ratio. As illustrated in Fig. 7, the microstrip antennas with thin slot and YIG material generate left-handed circular polarization. It is observed through the current distribution that rotates counter-clockwise on the surface of microstrip antenna at the corresponding four phases. From the simulated axial ratio (AR) plotted in Fig. 8, it is shown that at the resonant frequency, the microstrip antennas with thin slot and YIG material have AR value less than 3 dB, which indicates that the antennas have circular polarization capability. In comparison to the conventional one, the value of AR was improved from 0.9230 dB to 0.1094 dB and 0.0847 dB for microstrip antenna with thin slot and YIG material, respectively. Moreover, the 3 dB AR bandwidth also enhanced from 55.4 MHz to 62.4 MHz and 145.6 MHz at the operating frequency of 3.8352 GHz to 3.8977 GHz and 3.847 GHz to 3.9926 GHz for microstrip antenna with thin slot and YIG material, respectively. The polarization characteristics improvement of microstrip antenna with YIG material is evoked by the interaction of electromagnetic fields and internal magnetic bias from YIG material embedded in the antenna substrate.

TABLE I
PERFORMANCE COMPARISON OF MICROSTRIP ANTENNAS.

antenna design	f_{BW} (%)	–10dB imp. BW (MHz)	3dB ARBW (MHz)	Peak gain (dB)
conventional	3.1	127.2	55.4	4.6
with thin slot	5.8	227.5	62.4	4.6
with YIG material	4.6	183.6	145.6	4.5



(a)



(b)

Fig. 7. Simulated current distributions on microstrip antenna surface, (a) with thin slot, (b) with YIG material.

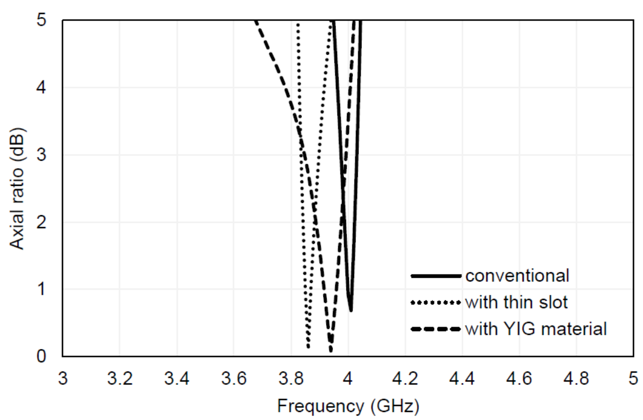


Fig. 8. Comparison of simulated axial ratio.

The performance comparison of microstrip antennas is summarized in Table I. It is pointed out that the microstrip antenna with thin slot has the widest –10dB impedance bandwidth with the fractional bandwidth (f_{BW}) of 5.8%. This is much wider compared to the conventional one and the microstrip antenna with YIG material. Moreover, it is also expected that by adjusting number of slots, bandwidth response could be enhanced. Meanwhile, although the microstrip antenna with YIG material provides less impedance bandwidth over the microstrip antenna with thin slot, the fractional bandwidth still shows the improvement compared to the conventional one. Despite the fact that the YIG material has small size in comparison to the radiating patch, utilization of magnetic material shows the potentiality in controlling radiation characteristics, in which the radiation pattern and the peak gain can be maintained at the resonant frequency. Additionally, in order to experimentally characterize the microstrip antenna with YIG material, 3D printing technology can be implemented for the antenna realization with low cost and easy fabrication. By using this technology, a small piece of magnetic material can be embedded into the antenna substrate by pausing the 3D printer in the midway of printing process and resume it afterward to complete the antenna structure. Hereafter, metallic surface coating is required in post-processing of antenna realization.

IV. Conclusion

The performance enhancement of circularly polarized microstrip antenna using thin slot and magnetic material has been presented. Two proposed configurations of microstrip antenna have been employed for investigating the antenna performances. The results showed that the microstrip antenna with YIG material embedded in the antenna substrate could improve bandwidth response, as well as microstrip antenna with thin slot, compared to the conventional one. Moreover, YIG material can be chosen as alternative way in producing and/or improving the radiation characteristics of microstrip antenna, in particular, circular polarization capability as it was able improving axial ratio at the desired resonant frequency with 3 dB AR bandwidth wider than the conventional one and the microstrip antenna with thin slot, while maintaining the radiation pattern and the gain as well. In addition, the proposed method has also shown the possibility of implementation for attaining tunable resonant-frequency. For the future work, the effect of varying position of magnetic material to the performances of microstrip antenna will be investigated and experimentally characterized.

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