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Miniaturized Microstrip Patch Antenna on YIG Material Under External Magnetic Field

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Abstract. This paper discusses an electrically small microstrip patch antenna that utilizes biased yttrium iron garnet (YIG) ferrite material. The study explores how the presence of an external magnetic field influences the bandwidth and radiation properties of the patch antenna. The antenna design is focused on operating at a frequency of 1.5 GHz. The utilization of biased YIG magnetodielectric material in the patch antenna results in an approximate threefold reduction in size compared to a patch antenna based on FR4 dielectric. Additionally, the antenna achieves a remarkable threefold increase in bandwidth, reaching 280 MHz at 1.5 GHz center frequency.

Keywords: electrically small antenna, microstrip patch antenna, YIG material, external magnetic field

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1. Introduction

Electrically small antennas (ESAs) have gained popularity because of their compact size and capacity for integration onto microchips. Small antennas are mainly used for mobile communication and other wireless systems such as detection, identification and etc [1]. However, there are fundamental limitations in the design of electrically small antennas (ESAs) that pertain to achieving a low Q-factor, impedance matching, and attaining high radiation efficiency. Several methods have been developed to design miniaturized antenna but with limited success. Currently, high dielectric constant and low-loss materials are used as substrates in the fabrication of miniaturized antennas. Although miniaturization can be achieved using high permittivity dielectric materials, there are some disadvantages: the existence of highly confined field around the substrate results in narrow band and lower efficiency of antenna, characteristic impedance in a high permittivity medium is low which makes it difficult to realize impedance matching between sources and antennas [2-3]. A promising approach to miniaturize antennas and address the previously mentioned issue is by utilizing magneto-dielectric materials (MDM) and ferrites [4]. It has been demonstrated that incorporating magnetodielectric materials into patch antennas increases their bandwidth by mitigating the concentration of electric current distribution across the antenna's surface and wider bandwidth is achieved using MDM in case of $\mu_r > \varepsilon_r$ [5]. There are many possibilities and combinations for using ferrite materials in printed antenna systems. They can be used as single substrate, in multilayer substrate configurations or with bias fields applied in different directions. For many years these unique properties of ferrite materials have found application in nonreciprocal and/or controllable microwave components such as isolators, circulators, phase shifters, switches, and tunable resonators [6-7]. The objective of this paper is to examine the use of biased YIG substrates in electrically small microstrip patch antennas.

2. Problem Statement

In this paper, an electrically small Yttrium Iron Garnet (YIG) ferrite-based patch antenna is studied. Fig.1 shows the top view of the structure of YIG based patch antenna. Yttrium Iron Garnet (YIG) is a crystal that has very high Q characteristics. YIG is a ferrite material that resonates at microwave frequencies when immersed in external field. The resonance is directly proportional to the strength of the applied field and has very linear tuning over multi-octave microwave frequencies. These materials have a permeability tensor whose elements can be easily controlled through the use of an external magnetic field. This can be done either by a sinusoidal magnetic field or by an impulse magnetic field [8-11].

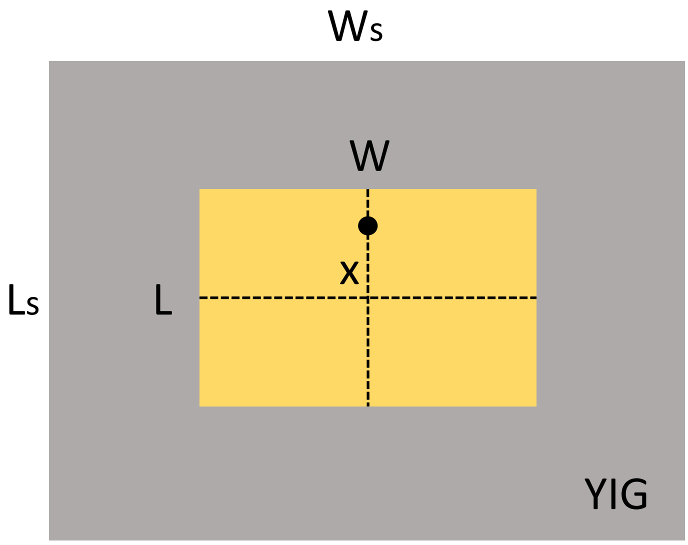

Fig. 1. The structure of microstrip patch antenna.

Regarding the unbiased ferrite, the magnetic permeability values versus frequency were computed based on Schloemann's equation for completely unbiased ferrites [12]:

$$\mu_r = \frac{2}{3}\sqrt{1-\left(\frac{\gamma\cdot 4\pi M_s}{\omega}\right)^2}+\frac{1}{3}\ , \tag{1}$$

where γ is gyromagnetic ratio, ω is frequency and $4\pi M_s$ is saturation magnetization. As shown in Equation (4), the magnetic permeability of YIG material can be adjusted by saturation magnetization.

Patch antenna size is generally determined by the wavelength in the antenna material [13]:

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r \mu_r}}\ . \tag{2}$$

By applying external magnetic field (Fig.2), thus adjusting magnetic permeability, patch antenna resonance frequency is controlled. It has been demonstrated experimentally in different works that the resonant frequency of a microstrip antenna printed on a ferrite substrate can be tuned over a 40% frequency range by adjusting the applied dc magnetic bias field [8].

This feature also allows to steer the main lobe of the radiation pattern and change the antenna polarization [14].

In another hand, patch antenna bandwidth strongly depends on $\frac{\mu_r}{\varepsilon_r}$ relations [15]:

$$BW = \frac{96\sqrt{\frac{\mu_r h}{\varepsilon_r \lambda_0}}}{\sqrt{2}(4+17\sqrt{\varepsilon_r \mu_r})}, \quad (3)$$

where h is height of substrate, λ_0 is a free space wavelength.

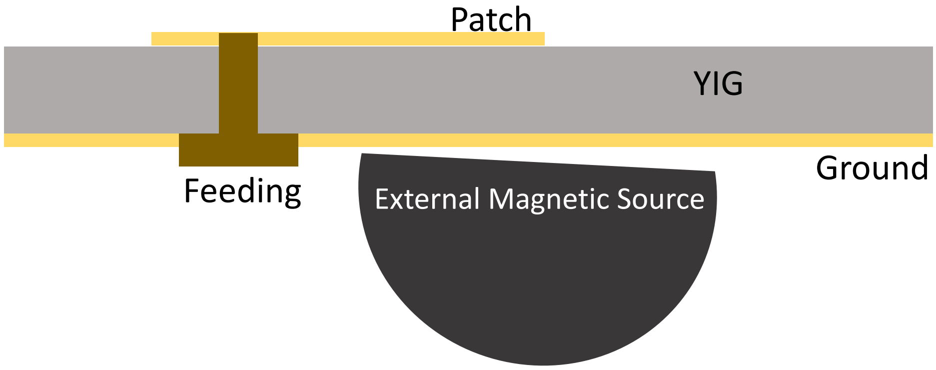

Fig.2. YIG ferrite microstrip patch antenna under external magnetic field.

Thus, the using of biased YIG material, electrically small antenna is achieved with improved bandwidth and its resonance frequency can be controlled via saturation magnetization of external magnetic field.

3. Results and Discussions

Microstrip patch antenna based on YIG material is designed, fabricated and main parameters are investigated. Antenna is designed at 2.4 GHz center frequency. The used YIG substrate parameters at 2.4 GHz frequency are: dielectric permittivity $\varepsilon_r = 12.8$, $4\pi M_s = 800$ Gs, $\Delta H = 10$ Oe. Patch antenna sizes are calculated [25] when the substrate height is $h = 1.6$ mm: patch width - $w = 22$ mm, patch length - $L = 30$ mm; feed position from the center - $x = 5$ mm; substrate width - $w_s = 40$ mm; substrate length $L_s = 48$ mm. Antenna scattering and radiating characteristics are measured using R&S ZVA40 Vector Network Analyzer. Fig.3 shows reflection coefficient of YIG based patch antenna. Because of the high Q-factor of YIG material, antenna bandwidth is very low (2 MHz). At 2.4 GHz frequency, reflection coefficient is $S_{11} < -10$ dB.

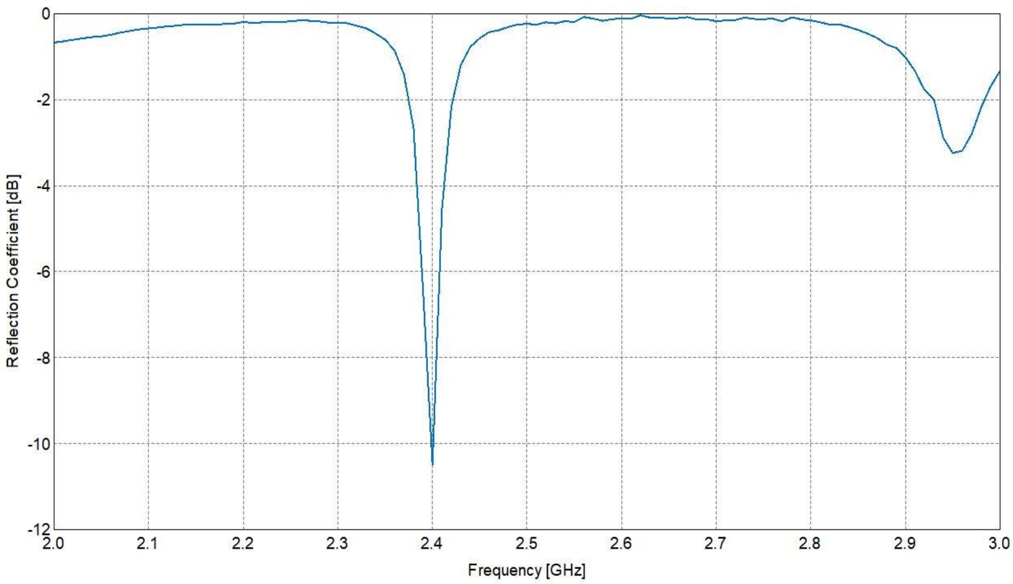

Fig. 3. YIG based microstrip patch antenna reflection coefficient.

Fig.6 demonstrates YIG based patch antenna radiation pattern at 2.4 GHz frequency. At 2.44 GHz antenna gain is 0.7 dBi, radiation pattern beamwidth: $2\theta_{0.5} = 82°$, side lobe level: $SLL = 12$ dB. The magnetic losses of YIG material are high in high frequencies which causes low gain.

By applying external magnetic field using a neodymium hemispherical magnetodielectric material with $r = 10$ mm radius above the patch antenna or ground (Fig.2), it is observed a reduction in the center frequency to 1.5 GHz (see Fig.4), along with a wide 500 MHz impedance bandwidth (1.33 - 1.83 GHz) where reflection coefficient $S_{11} < -10$ dB. Relative bandwidth of antenna is $\delta = 33.3$ %. Fig.5 demonstrates biased YIG-based patch antenna gain versus frequency. At 1.5 GHz antenna gain is -5 dBi. At 1.4 – 1.68 GHz frequency range (280 MHz bandwidth) antenna gain is in range of -6 to -3 dBi. Antenna gain is low since known relationship between it and the effective antenna radius $D = kR^2$. This relationship imposes limitations on achieving high values of directivity on small antennas [16].

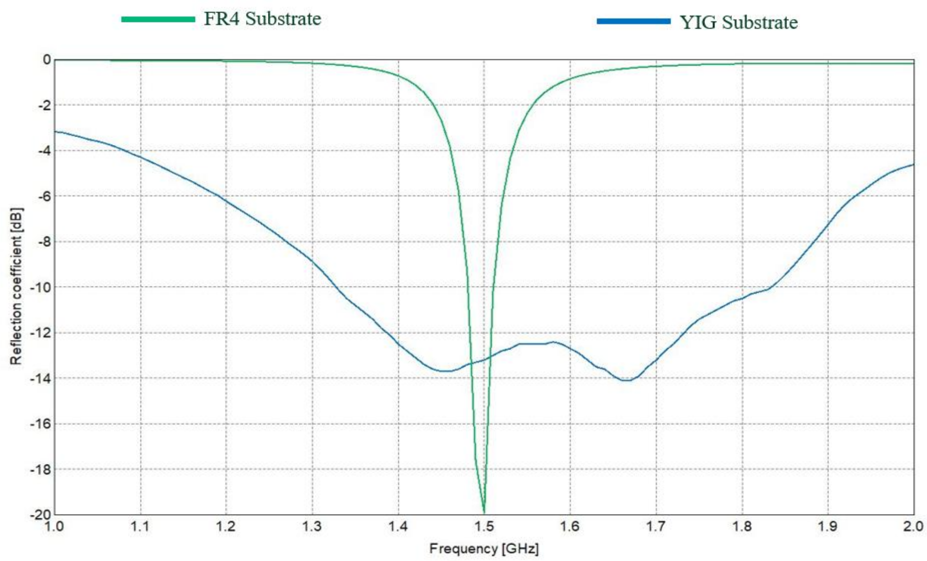

Fig. 4. Biased YIG based and FR4 based microstrip patch antennas reflection coefficient

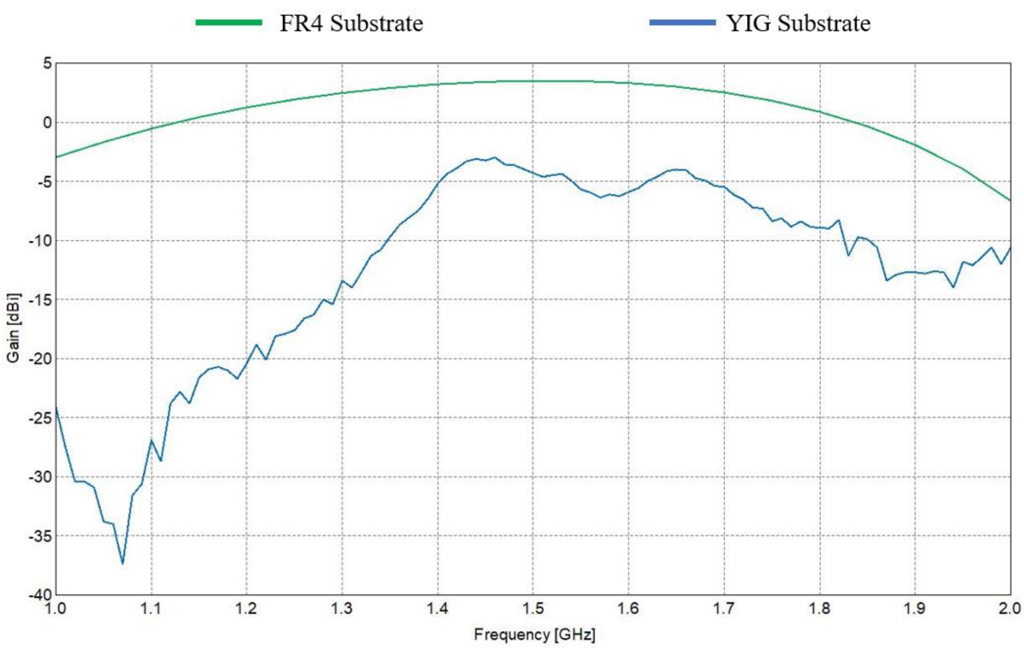

Fig. 5. Biased YIG based and FR4 based microstrip patch antenna gain.

A comparative analysis was carried out between an YIG-based electrically small antenna anda microstrip patch antenna designed on an FR4 substrate with $\varepsilon_r = 4.6; tg\delta = 0.017$ parameters. FR4-based patch antenna is designed at 1.5 GHz center frequency. The antenna dimensions are: $W = 45.2$ mm, $L = 58.2$ mm, $x = 1$ mm, $W_s = 70.8$ mm; $L_s = 83.8$ mm. The antenna has a bandwidth of 30 MHz (1.48-1.51 GHz) where $S_{11} < -10$ dB and gain $G = 3.2$ dBi as shown in Fig.5. Compared with FR4 based patch antenna, YIG-based antenna exhibits better bandwidth (more than 9 times), despite having surface area 3 times smaller. Certainly, the gain is compromised by more than 6 dB due to the antenna's small dimensions.

The red line of Fig.6 demonstrates a YIG based patch antenna radiation pattern at 1.45 GHz frequency where antenna gain is maximum. At this frequency antenna gain reaches -3 dBi, with 92° beamwidth and $SLL = 8.8$ dB side lobe level. The compact size of the antenna results in a larger beamwidth and a smaller SLL compared to a YIG-based antenna without an external field.

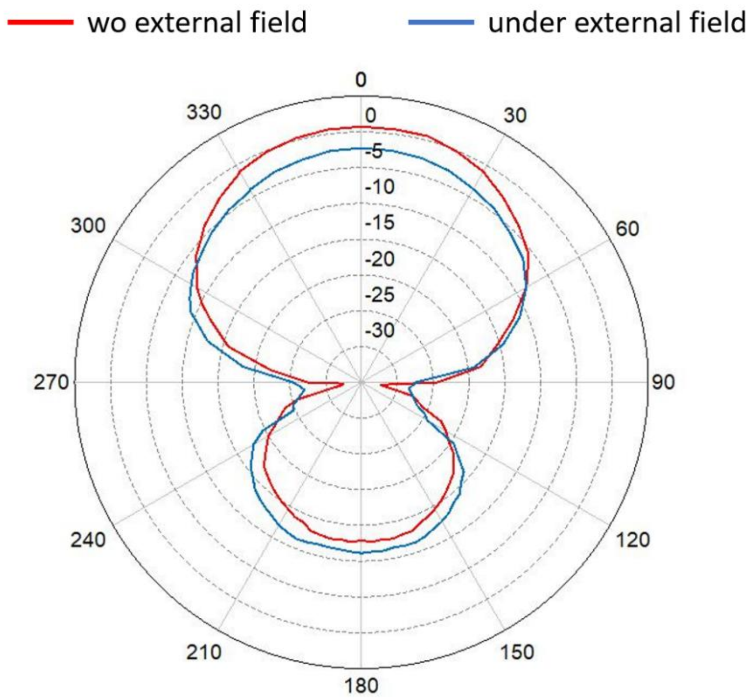

Fig. 6. Antenna radiation pattern, without external field at 2.4 GHz frequency (red line), under external field at 1.5 GHz (blue line).

4. Conclusions

Thus, this study explores the utilization of YIG materials to achieve electrically small patch antenna. YIG materials have the unique feature of enabling control over magnetic permeability through the external magnetic field. This control allows for a reduction in the operating frequency of the patch antenna and an improvement in its bandwidth. It's initially considered an unbiased YIG-based patch antenna with an operating frequency of 2.4 GHz. However, there are limitations due to the high Q-factor and material losses, resulting in significantly reduced bandwidth and gain.

To address these limitations, an external magnetic field is applied to the YIG material, significantly influencing the antenna's performance. Consequently, the antenna's operating frequency range is shifted to a lower range, from 1.33 to 1.83 GHz, providing a broader 500 MHz impedance bandwidth.

Despite the advantages in bandwidth, the biased YIG-based antenna gain is low, because of the relationship between gain and antenna size, with a range of -6 to -3 dBi in 280 MHz bandwidth.

As a result of the external magnetic field application, the patch antenna originally designed to operate at 2.4 GHz now functions at a significantly lower frequency, reduced by 44.58%. Compared with FR4-based patch antenna, the biased YIG-based patch antenna demonstrates a substantial ninefold increase in bandwidth, within a more compact form factor, being three times smaller.

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