Tunable Inkjet-Printed Slotted Waveguide Antenna on a Ferrite Substrate

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***Abstract*—In this work an inkjet-printed frequency-tunable slotted waveguide antenna on a ferrite substrate is reported. Unlike the typical substrate integrated waveguide approach with via holes, a true 3D rectangular waveguide is realized by inkjet-printing of nano-particle based conductive ink on the broad faces as well as on sides of the substrate. The operating frequency of the antenna can be tuned by applying a variable static bias magnetic field that controls the permeability of the host ferrite substrate. The antenna operates about a center frequency of approximately 14 GHz with an instantaneous impedance bandwidth of 75 MHz. A fabricated prototype has demonstrated a tuning range of 10% (1.5 GHz) using an applied bias magnetic field of 3 kOe yielding it especially attractive for tunable and reconfigurable yet low cost microwave systems.**

***Index Terms*—Inkjet printing, slotted rectangular waveguide, tunable antenna.**

I. Introduction

There is a continuous demand for smart reconfigurable antennas to be employed in modern communications systems with adaptive front ends. Frequency-tunable antennas are particularly attractive for multi-band communication systems as well as systems that require frequency hopping such as radars. A single frequency-agile antenna can replace multiple antennas inside such a system, reducing size and cost [1], [2]. It is thus desirable to find new frequency-tunable antennas that can be fabricated through low cost and scalable processes.

Inkjet printing is a new fabrication technique for low cost production of electronic systems. Due to its additive nature, it reduces material wastage and is thus an environment friendly process. In addition, it is much simpler and cheaper when compared to conventional photolithography based process which requires use of expensive masks and harsh chemicals for etching in an expensive clean room environment. Furthermore, inkjet printing can be used for mass production of electronics system by roll-to-roll printing. Several inkjet printed devices have appeared in the literature recently, such as filters, couplers and antennas [3], [4].

Rectangular waveguides are fundamental components for microwave engineers, they can be used to realize multitude of circuits and antennas. Of which, rectangular waveguide slot antennas have been extensively used in variety of applications due to their reliability and ease of scaling into array format [5]. However, they are bulky, non-planar and difficult to integrate with planar circuitry. On the other hand, Substrate Integrated Waveguides (SIWs), though planar and integrable, require extensive micro-machining to realize rows of vias at sub-wavelength pitch to reduce wave leakage from the SIW sides. Recently, a true rectangular waveguide ferrite isolator has been realized through inkjet printing [6], this demonstration showed the possibility of realizing tunable waveguide-based components through inkjet-printing.

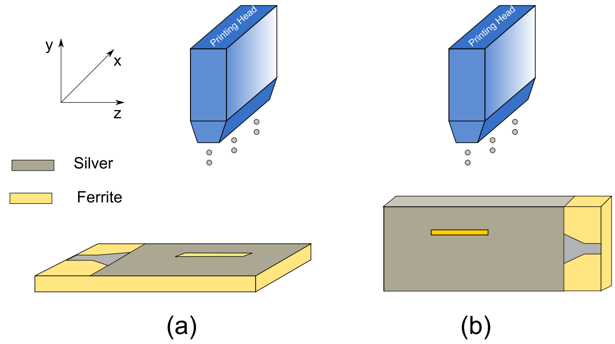


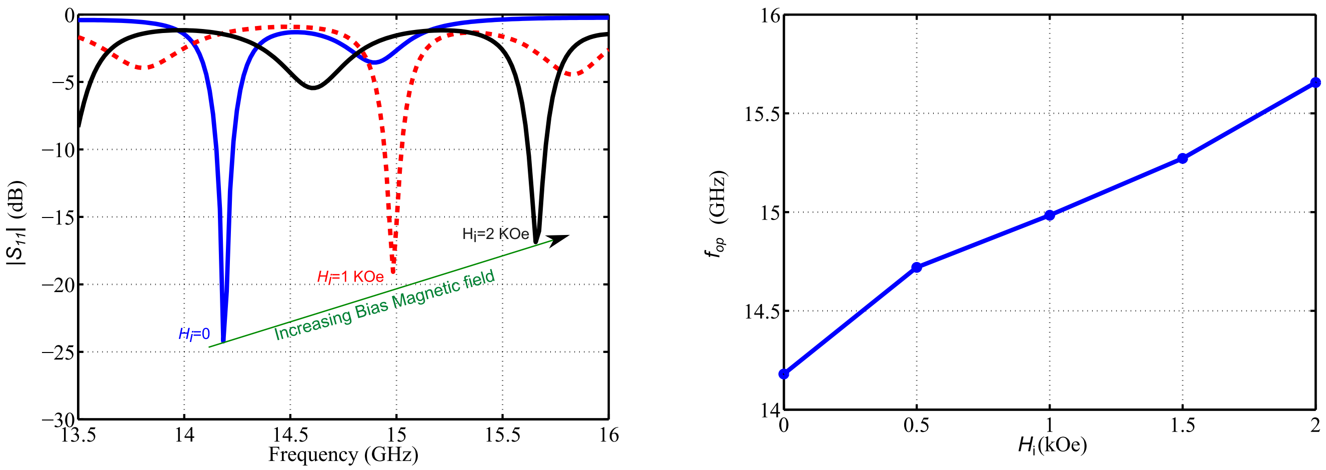
Fig. 1: Inkjet Printing of a rectangular waveguide. (a) Top metalization pattern. (b) Side metalization pattern.

In this work, we use magnetically-tunable ferrite material as a host substrate for a slotted waveguide antenna to achieve the frequency-tuning functionality. A true rectangular waveguide is realized by inkjet printing on all four faces of the ferrite substrate in a 3D fashion as illustrated in Fig. 1. This approach eliminates the requirement of substrate machining for making vias which is not a simple process for the case of brittle ferrite substrates and it also ensures no wave leakage from the sides as compared to a SIW.

II. Rectangular waveguide Slot antenna Design

A. Theory of operation

A slotted waveguide antenna is designed to operate in Ku-band on a 0.4 mm-thick Yttrium Iron Garnet (YIG) ferrite substrate. At no bias (completely demagnetized) the YIG substrate is characterized by a scalar dispersive permeability, given in [7], whose value is about 0.96 at 14 GHz. When magnetized by the application of a magnetic field the material permeability has the form of a gyrotropic tensor, for a magnetically saturated ferrite the elements are given in [8]. These elements are all dependent on the internally established magnetic field (H_i), which can be controlled by changing the applied magnetic field to the material using an electromagnet.



(a) (b)

Fig. 2: Simulated frequency-tuning of the slotted waveguide antenna. (a) Reflection Coefficient. (b) Operating frequency versus bias field.

For a transversely biased rectangular waveguide (y-direction in Fig.1(a)), the structure supports a TE_{10}-like mode with a scalar effective relative permeability given by :

$$\mu_e = \frac{f^2 - f_z^2}{f^2 - f_p^2} \quad (1)$$

with $f_z = f_m + f_0$, $f_p = \sqrt{f_0 f_z}$, where $f_m = (2.8\text{MHz/Gauss}).M_s$ is the material's magnetization frequency and $f_0 = (2.8\text{MHz/Oe}).H_0$ is the gyromagnetic resonance frequency. As the internal magnetic field is increased, the effective permeability drops in value. This causes the resonance frequency of slot to increase to a higher frequency ($f_{res} \approx \frac{c}{2L_{slot}\sqrt{\epsilon_r \mu_{eff(H)}}}$).

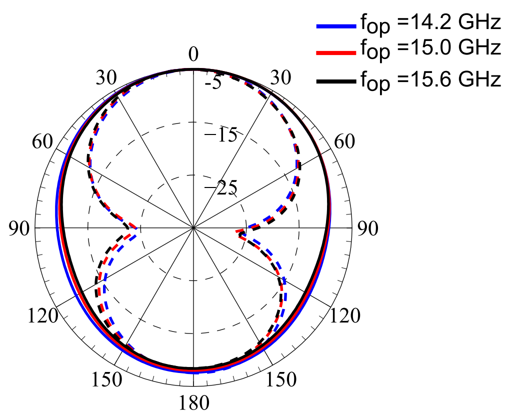


Fig. 3: Radiation pattern at at different operating frequencies, E-plane (solid-lines) and H-plane (dashed-lines).

B. Simulation Results

A rectangular waveguide slot antenna fed using a microstrip line tapered transition, depicted in Fig. 1, has been optimized for operation in Ku-band using CST microwave studio [9]. The waveguide is terminated with a short circuit and a longitudinal shunt slot is placed at a distance of $3\lambda_g/4$ from it to induce broadside radiation. The antenna operating frequency (f_{op}) tunes over a range of about 1.5 GHz starting at 14.16 GHz up till 15.66 GHz when the bias field is increased till 2 kOe as illustrated in Fig.2. A matching better than -10 dB is maintained for all bias fields with an instantaneous impedance bandwidth of nearly 75 MHz. The radiation pattern is stable as the frequency is tuned with very little variation as depicted in Fig.3, the gain of the antenna also shows little variation with bias being approximately -5 ± 0.5 dB. The generally low gain value is attributed to the losses due to the low conductivity of the silver ink (1×10^7 S/m) as well as the high permittivity of the YIG substrate ($\epsilon_r = 15$). Nevertheless, the gain value can be increased by using better conductive ink as well as lower permittivity ferrite substrates.

C. Fabrication and Measurements

The antenna is inkjet printed on the YIG substrate using the Dimatix 2831 materials printer. Silver nanoparticle based ink with average particle size of 150 nm dispersed in organic solvent having 20% silver concentration by weight is used for printing. Before printing, it is necessary to clean the YIG substrate by acetone to remove oils, grease or any other contaminants which can greatly affect the printing quality. The conductivity of the printed metal can be increased by printing multiple layers of ink. Fig. 4 shows the sheet resistance of printed silver on YIG substrate against the number of layers. It can be seen that resistance is pretty high for only one layer of ink and decreases significantly by printing more number of layers till it saturates. Four layers of ink are printed to realize the waveguide slot antenna giving a sheet resistance of 0.5 /sq. All five walls of the waveguide, along with the microstrip to waveguide transition, have been inkjet printed to realize the antenna. Each wall is printed by orienting the YIG substrate such that the side to be printed is facing the printer nozzles.

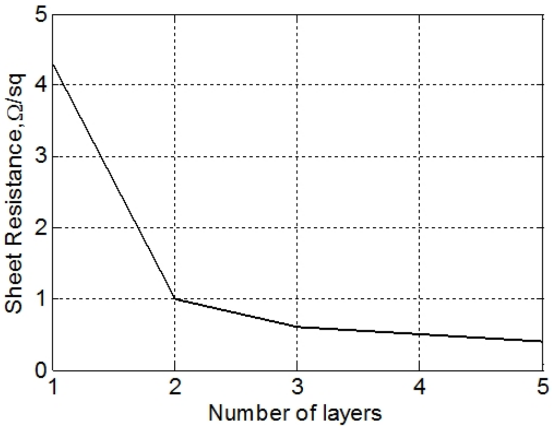
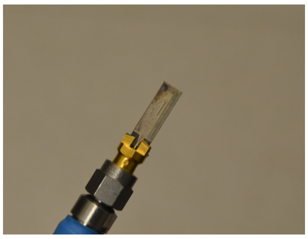


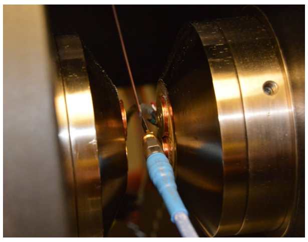
Fig. 4: Sheet resistance of the printed metal.

After printing, the substrate is heated to 180 °C for 30 minutes in order to sinter the nanoparticles to form continuous metal tracks.

The fabricated prototype is shown in Fig. 5. Impedance measurement has been carried out by using an electromagnet for varying the applied magnetic field over a range from 0 to 3 kOe. The results, shown in Fig. 6, show good correlation to simulated ones and confirm that about 10% tunning range is achieved in this configuration.



(a)

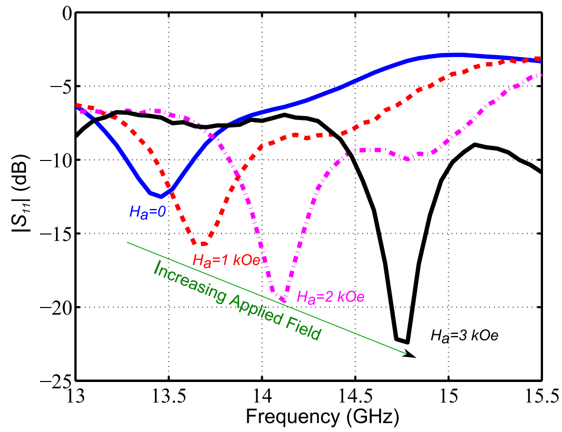


(b)

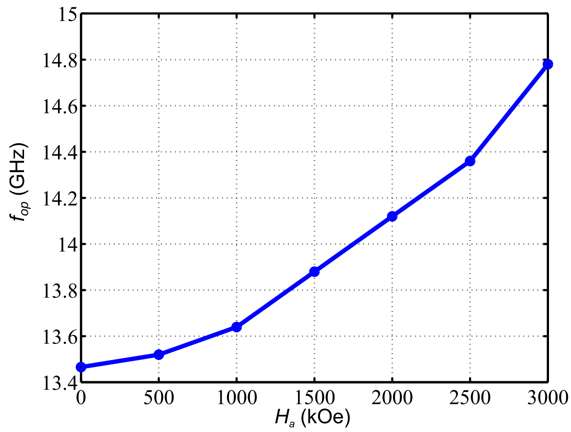
Fig. 5: (a) Fabricated prototype. (b) Prototype between electromagnet poles for tuning.

III. Conclusion

In this work, a frequency-tunable rectangular waveguide slot antenna has been demonstrated using inkjet-printing technique. The slot antenna has been designed and realized on a ferrite substrate, over a 10% tuning range in Ku-band has been demonstrated in measurements using an applied bias magnetic field of 3 kOe.



(a)



(b)

Fig. 6: Measured frequency-tuning of the slotted waveguide antenna. (a) Reflection Coefficient. (b) Operating frequency versus bias field.

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