Bandwidth Design of Ferrite-Based Circulators

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***Abstract*—This paper reports on the RF design of planar ferrite-based RF circulators with bandwidth control through the height of the ferrite-puck and the DC magnetic biasing. The analysis is performed with the aid of a commercially-available finite-element solver for a design frequency of 3.9 GHz. The study reveals that by varying the ratio of ferrite height to substrate height within the circulator cavity from 0.1 to 1, the 1-dB bandwidth varies between 5 and 36.2%. While conventional RF circulators are designed for a fill factor equal to 1, this study shows that maximum bandwidth is obtained for a fill factor of 0.82.**

***Index Terms*— Circulator, fractional bandwidth, magnetic bias, insertion loss, isolation.**

I. Introduction

Recent advances in high power radar systems call for high levels of isolation between the transmit and received RF signals within a broad bandwidth of operation. In order to meet these requirements, low-profile and broadband RF circulators need to be developed [1]. However, the majority of commercially-available planar-based circulators exhibit fractional bandwidths (FBWs) below 20% [2]-[4]. Alternative RF design techniques have been developed with the purpose of increasing FBW. These include, adding multi-section matching networks at the input/outputs of the ferrite-puck or by routing the RF signal between inter-coupled ferrite-loaded cavities [4]. However, these techniques result in large physical size and excess of RF loss.

This paper examines the FBW design limits of microstrip-type circulators loaded by circular ferrite pucks. The proposed study focuses on single cavity circulators and analyzes the effects of altering the ferrite material fill factor H_P/H_S within the circulator cavity, as shown in Fig. 1. Commercially-available ferrite pucks from TransTech (TT1-105) and a dielectric substrate from Rogers (4350) are considered for all devices. The proposed study reveals that by altering the ferrite's fill factor, the FBW of the circulator can be tailored between 5-36.2% with the maximum FBW obtained for a fill factor of 0.82.

II. Fill Factor Study

The RF design of ferrite-based microstrip circulators has been widely discussed in the open technical literature and is summarized in this section. For a uniformly applied DC magnetic bias field— above magnetization saturation M_S —and a defined set of material parameters including: relative permittivity ε_r, relative permeability μ_r, linewidth of the ferromagnetic resonance ΔH and a desired design frequency f_0,

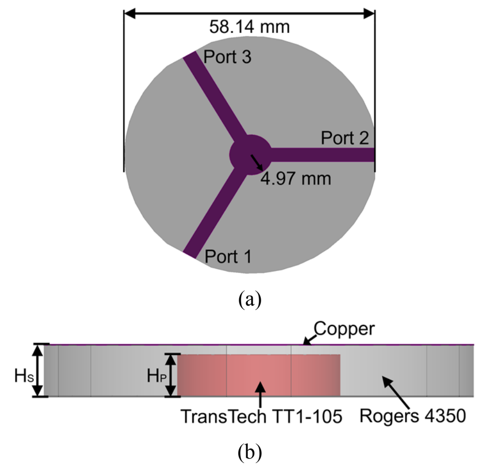

Fig. 1. (a) Top view. (b) Cross-sectional view of the microstrip-line type circulator. The material properties are summarized as follows: Dielectric substrate: Rogers 4350, ε_r=3.66, H_S=1.524 mm, Ferrite puck: TransTech TT1-105: M_S=0.175T, ε_r=12.2, μ_0=55, ΔH=220 Oe, $H_P \leq 1.524$ mm. The conceptual drawings of the circulator are not in scale.

the radius of the ferrite puck can be calculated using (1):

$$R_f = \frac{1.84}{2\pi f_0 \sqrt{\varepsilon_r \mu_{r,eff}}} \quad (1)$$

where $\mu_{r,eff}$ denotes the effective permeability that is a function of f_0 and magnetization.

For the sake of comparison, a baseline circulator architecture is designed for a frequency of 3.9 GHz and 50 Ω reference impedance using as a basis the material parameters in Fig. 1 and the design methodology in [1]. Furthermore, the ferrite's height H_P is set equal to the height of the dielectric substrate H_S,

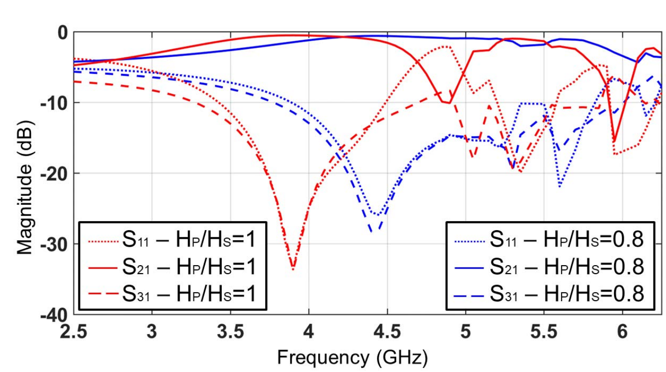

Fig. 2. Electromagnetically-simulated response in terms of S-parameters for alternative levels of H_P/H_S. The circulator dimensions and the applied DC magnetic bias field are identical for both designs.

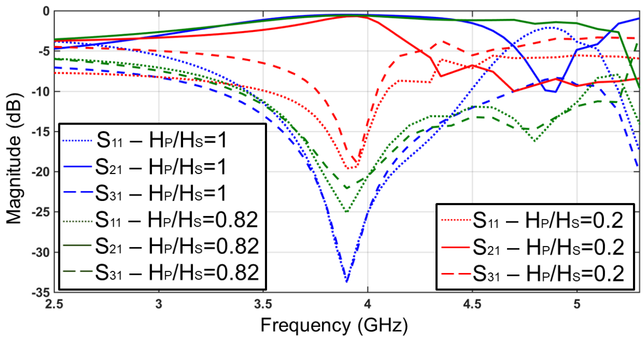

Fig. 3. Electromagnetically-simulated response in terms of S-parameters for alternative levels of H_P/H_S. The circulator dimensions are identical for both designs. The DC magnetic bias field is altered as shown in Fig. 4.

resulting in a fill factor of 1. Its simulated response is obtained using the commercially available finite-element-based software ANSYS HFSS and is illustrated in Fig. 2. It exhibits a 1-dB-bandwidth of 1.1 GHz, FBW of 28.1%, minimum insertion loss and maximum isolation of 0.51 dB and 33 dB respectively.

The ferrite fill factor effect is studied by altering the ratio of H_P/H_S whilst keeping the rest of the circulator dimensions constant. A comparison for two different values of the fill factor, 1 and 0.8 is shown in Fig. 2. It can be seen that by reducing the fill factor from 1 to 0.8, the operational frequency of the circulator shifts to higher frequencies whereas its bandwidth broadens. In order to better compare the circulator designs, they are redesigned for the same center frequency. This is achieved by altering the DC magnetic bias field from 142 KA/m to 108 KA/m (below M_S) which results in both designs operating at the same center frequency of 3.9 GHz.

The overall RF performance of the circulator for various fill factors H_P/H_S is shown in Figs. 3, 4 in terms of S-parameters, FBW and magnetic bias. It can be seen that by altering H_P/H_S from 0.1 to 1 and the magnetic bias between 108-142 KA/m, the FBWs can be designed between 5% and 36.2%. This effect proves that the proposed RF design technique is suitable for the realization of both narrowband and broadband circulators in which the resonator footprint is identical. It should be highlighted that although conventional circulator designs have H_P/H_S=1 [4], maximum FBW is obtained for H_P/H_S <1 which is 0.82 in this case. However, the maximum FBW state exhibits 10 dB less isolation than the baseline design (H_P/H_S=1). Furthermore, for fill factors that are set <0.82 (FBW maximum), the following trends can be observed. The FBW becomes narrower with the decrease of H_P/H_S, whereas the insertion loss increases and the isolation decreases.

III. Conclusion

This paper reports on the RF design of ferrite-based microstrip-type circulators with narrow and broadband width. The analysis considers ferrite-based pucks with fill factor ≤ 1 and alternative levels of DC magnetic biasing that was modified with the purpose of altering the circulator bandwidth, without affecting its operational frequency. The presented study reveals that by altering the ferrite fill factor within the circulator cavity from 0.1 to 1, the 1-dB bandwidth varies between 5 and 36.2%. While conventional RF circulators are designed for a fill factor

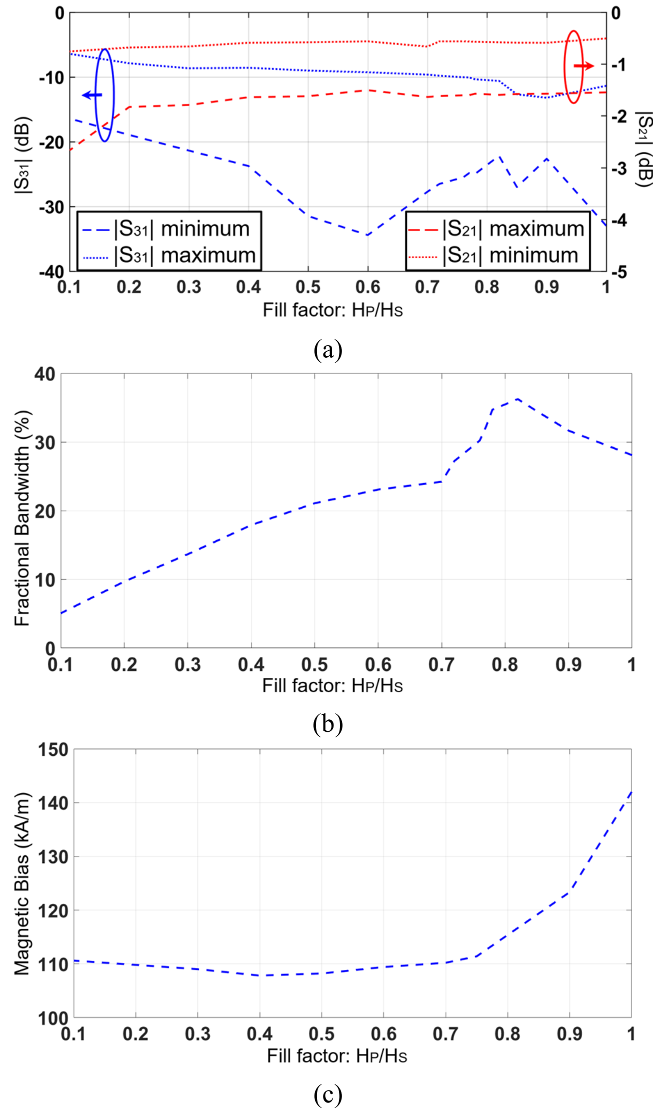

Fig. 4. Circulator performance for alternative levels of H_P/H_S. (a) Power transmission response: S_{21}, S_{31}, (b) FBW, and (c) DC magnetic bias.

equal to 1, this study shows that maximum bandwidth can be obtained for a fill factor <1. For the specific materials considered here, this value is 0.82.

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