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Design and fabrication of self-biased millimeter wave circulator using barium ferrite thin films

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Abstract: A millimeter wave film circulator with coplanar waveguide structure was designed and fabricated using barium ferrite films with thickness of 10 μm. The film circulator operates without external magnet and shows clear circulation at 34 GHz and 37.6 GHz. Circulation with non-reciprocal effect greater than 15 dB has been observed. The results show that circulator using very thin ferrite films can be realized with coplanar waveguide structure. The film circulator exhibits potential to be integrated with MMIC.

Key words: circulators; ferrite films; self-biased; coplanar waveguide
PACS: 84.40.-x, 85.70.Ge, 95.70.Kh

钡铁氧体薄膜自偏置毫米波环行器设计与制备

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摘要:基于厚度为10 μm的钡铁氧体薄膜设计,制备了共面波导结构的毫米波薄膜环行器.这种薄膜环行器不需要外加磁体,在34 GHz和37.6 GHz显示出环行特性,其非互易效应大于15 dB.结果表明,采用共面波导结构可以实现薄膜环行器.这种薄膜环行器具有和单片微波集成电路集成的潜在应用.

关 键 词:环行器;铁氧体薄膜;自偏置;共面波导
中图分类号:TN61 **文献标识码**:A

Introduction

Microwave circulator is one of the most important components of T/R module in Monostatic Radar system. Hexagonal ferrites, especially M-type barium ferrites (BaM), have high uniaxial magnetocrystalline anisotropy, which can produce suitable internal field so that barium ferrites have great potential applications in millimeter wave devices. At the same time, barium ferrites have large remanence. So microwave circulators using barium ferrites can operate without external magnets and is easy to be integrated with microwave circuits[1-4], thereby self-bias is realized and the size and weight of circulators were reduced significantly. To further reduce the size of the devices and integrated with MMIC, circulators with barium ferrite films were preferred.

Though ferrite circulators with bulk ferrites have been studied widely[1-6], circulators using ferrite thin film have a little progress. Recently, Zahwe et al[7] prepared a CPW circulator using YIG thin films with thickness of 15 μm on alumina substrate and found the circulation occurs at 10 GHz with insertion loss of 18 dB and isolation of 26 dB. However, in these CPW

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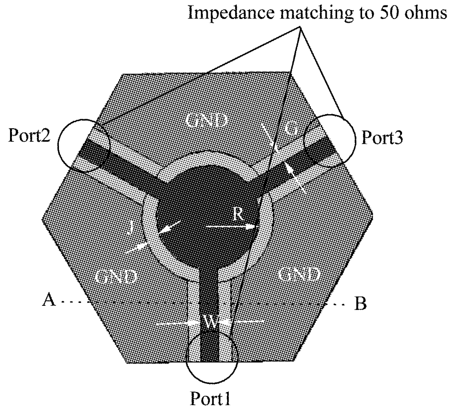
circulators, external magnets were required, which is an obstacle for size reduction of integrated devices. For self-biased circulators with CPW structure, only a few articles discussed about it. In 2007, Dehlinger et al[8] tried the self-biased circulator with CPW structure using 10 μm thick BaM films, which demonstrates a very weak non-reciprocal effect of 2.6 dB at 40 GHz.

In our earlier work, we have reported the design and the simulation results of self-biased coplanar circulator using BaM films[9-10]. In this work, self-biased film circulator with CPW structure was designed and fabricated using BaM films with thickness of 10 μm. Then the circulator was fabricated and measured. To the best of our knowledge, this is the first report of self-biased CPW circulator using barium ferrite films, which shows strong circulation behaviors.

1 Design and simulations

Figure 1 shows the structure of the film circulator with CPW design. According to Fig. 1(a), the self-biased circulator has a Y-junction and three ports. As shown in Fig. 1(b), a lower non-connected metal disk with radius of Rc is directly deposited on a sapphire substrate, which locates between the BaM films and the substrate. The signal line and the Ground (GND) plane of the self-biased circulator are placed on the BaM films with slots between the signal line and the GND plane.

The thickness of the BaM films and the sapphire substrate are 10 μm and 500 μm, respectively. The design parameters of the BaM films are: the dielectric constant $\varepsilon_r = 9.8$, the dielectric loss tangent $\tan\delta = 5\times10^{-4}$, the ferromagnetic resonance (FMR) linewidth $\Delta H = 50$ Oe, and the saturation magnetization $4\pi M_s = 4\,000$ Gs. The internal field (H_i) of BaM film is around 15 kOe, which was contributed by magnetocrystalline anisotropy field (H_A) and demagnetizing field, i. e., $H_i = H_A - NM_s$, where N is the demagnetization factor. The conductor line was made of gold with thickness of 3 μm. In our self-biased circulator, because no external magnetic field is applied, the ferrite films are not saturated. However, it was assumed that the BaM films were magnetized to saturation normal to the film plane in our design to simplify the design process.



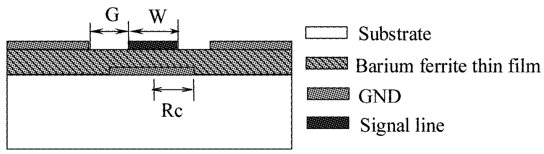


Fig. 1 Structure of the self-biased CPW circulator (a) top view, and (b) A-B cross section
图 1 自偏置 CPW 环行器结构(a)俯视图,(b)A-B 横截面

The detailed design procedure of the self-biased circulator with CPW structure was illustrated as in[9-10], which is based on the work of Bosma[11] and Comstock[12]. After optimization, the dimensions of self-biased circulator were obtained as following: the radius of the central conductor R = 1 mm, the width of the signal line $W = 0.18$ mm, the signal line to GND spacing $G = 0.1$ mm, the distance between GND plane and the signal line $J = 0.1$ mm, the radius $Rc = 1.1$ mm. The three ports of the circulator have been tuned to 50 Ω at the working frequency in order to match the circulator output impedances to test system. The designed circulator was simulated using HFSS software. The simulation results are shown in Fig. 2. The circulation characteristics can be found at 34.1 GHz. The insertion loss is about 1.8 dB while the isolation is greater than 19 dB.

2 Fabrication and measurements

Figure 3 schematically illustrated the fabrication procedure of the self-biased circulator with CPW structure. In Fig. 3(a), a lower non-connected Pt disk was prepared on the sapphire substrate by lift-off and magnetron sputtering techniques. The thickness of Pt disk

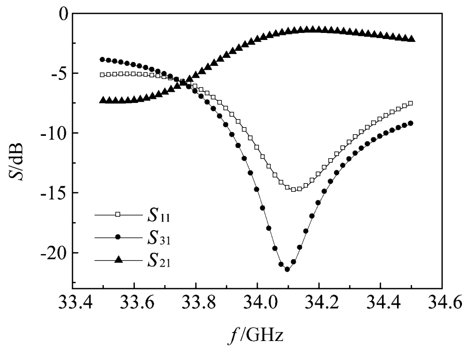


Fig. 2 Simulation results of the CPW film circulator
图2 CPW 薄膜环行器的仿真结果

was around 0. 1 μm. According to Fig. 3 (b) , a 10 μm thick barium ferrite film was directly sputtered on the sapphire substrate with the lower non-connected plane. The barium ferrite film was annealed in air at 1000 °C for 3 hours. Then surface gold layer was deposited by evaporation and following electroplate to enhance the thickness. The thickness of gold layer is 3 μmand is more than four times of the skin depth in gold. And then the signal line and GND plane were patterned by standard lift-off techniques as shown in Fig. 3(c).

A prototype of the self-biased coplanar circulator using BaM thin films according to the former design is prepared and a photograph of the samples is shown in Fig. 4. The transmission characteristics of the self-biased circulator with CPW structure were measured by Agilent N5230A vector network analyzer. In the measurements, a 50 Ω load was connected to the third port and the self-biased coplanar circulator was tested without external magnetic field. A short-open-load-thru (SOLT) calibration had been used before measurement.

3 Results and discussions

The measured S-parameters are shown in Fig. 5. We can see that there are large differences between S_{12} parameter and S_{21} parameter at certain frequency, which indicates that the film circulator shows obvious non-reciprocal effect. Two band circulation[2] between 30 ~ 40 GHz has been observed. The above-FMR circulation operates at 34 GHz with an insertion loss of 24 dB and an isolation of 43 dB. The below-FMR circulation occurs at 37.6 GHz with an insertion loss of 17 dB and an isolation of 33 dB. It can be seen that the film circulator shows a non-reciprocal effect greater than 15 dB.

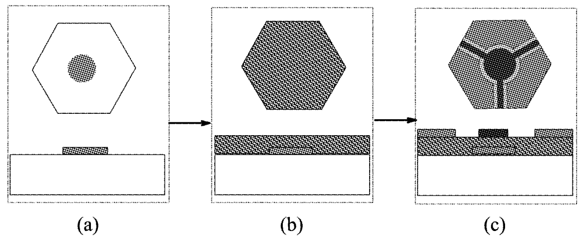


Fig. 3 The process of fabrication of self-biased circulator with CPW structure
图3 制备 CPW 环行器的工艺流程

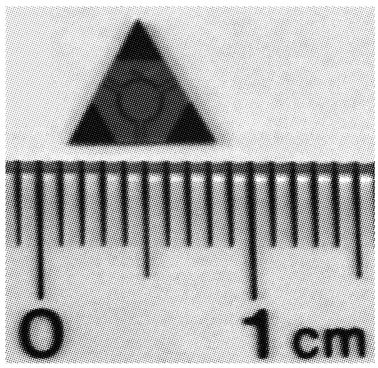


Fig. 4 Prototype of the self-biased coplanar circulator using BaM films
图4 钡铁氧体薄膜自偏置 CPW 环行器实物图

In Fig. 5 (a) , we can see the insertion loss is large. It is known that magnetic loss is one of the most important parts in the losses. The deposited BaM films are polycrystalline films, which have inherently wide FMR linewidth. This is the major source of the high insertion losses. Especially, when operating frequency is close to the FMR frequency the losses increase dramatically. In our work, the FMR frequency is about 36.4 ~ 39.2 GHz. From Fig. 4, we can see that the circulation frequency is near the FMR frequency, so the FMR losses are large.

At the same time, in our design, the ferrite films were treated as they had been saturated. But the ferrite films actually work in the remanent state. The hysteresis loops measurements show that the remanent ratio of the prepared BaM films is about 0. 6. Then magnetic domains and domain walls must exist in the BaM films,

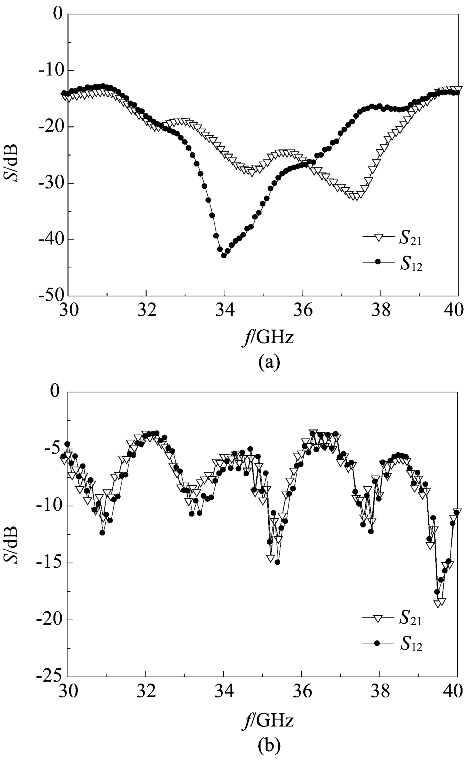


Fig. 5 Measured S-parameters of the self-biased film circulator. (a) S_{21} and S_{12}, (b) S_{11} and S_{22}
图 5 自偏置薄膜环行器测试结果(a) S_{21} 和 S_{12}, (b) S_{11} 和 S_{22}

which also contribute to the losses in the self-biased devices.

Another reason may be the impedance mismatch. Although the impedance matching has been realized in the simulations, the impedance is not well matched as shown in Fig. 5(b) due to the differences between the designed values and the real values of the material parameters such as dielectric constant and magnetocrystalline anisotropy field etc. The tolerances in the fabrication process can result in impedance mismatch.

Although the insertion loss of our film circulator is large, we have successfully demonstrated a self-biased film circulator showing strong circulation performance with a non-reciprocal effect greater than 15 dB at Ku band. With decrease of the losses in ferrite films and improvement of impedance matching, the losses of the circulator are expected to be decreased remarkably. When the annealing temperature of ferrite films is decreased by optimizing fabrication process, the film circulator with CPW structure in this work would exhibit great potential to be integrated with MMIC.

4 Conclusions

A self-biased CPW circulator using 10 μm thick BaM films has been designed and fabricated. The measured results show that the self-biased film circulator has below and above FMR circulation at Ku band. Circulation with non-reciprocal effect greater than 15 dB has been observed in the prepared film circulator. The self-biased film circulator exhibits potential to be integrated with MMIC. Further work is to reduce the insertion loss hindering practical applications of this film circulator.

REFERENCES

[1] Zuo X, How H, Somu S, *et al*. Self-biased circulator/isolator at millimeter wavelengths using magnetically oriented polycrystalline strontium M-type Hexaferrite [J], *IEEE Trans. Magn.*, 2003, **39**(5): 3160 - 3162.
[2] Shi P, How H, Zuo X, *et al*. MMIC circulator using hexaferrites[J], *IEEE Trans. Magn.*, 2001, **37**(4): 2389 - 2391.
[3] Oliver S A, Shi P, Hu W, *et al*. Integrated self-biased hexaferrite microstrip circulators for millimeter-wavelength applications[J], *IEEE Trans. Micro. Theory Tech.*, 2001, **49**(2): 385 - 387.
[4] Zeina N, How H, Vittoria C, *et al*. Self-biasing circulators operating at Ka-band utilizing M-type hexagonal ferrites [J], *IEEE Trans. Magn.*, 1992, **28**(5): 3219 - 3221.
[5] O'Neil B K, Young J L. Experimental investigation of a self-biased microstrip circulator[J]. *IEEE Trans. Micro. Theory Tech.*, 2009, **57**(7): 1669 - 1674.
[6] Oshiro K, Mikami H, Fujii S, *et al*. Fabrication of circulator with coplanar wave guide structure[J]. *IEEE Trans. Magn.*, 2005, **41**(10): 3550 - 3552.
[7] Zahwe O, Abdel Samad B, Sauviac B, *et al*. YIG thin film used to miniaturize a coplanar junction circulator[J]. *J. Electromagn. Waves Appl.*, 2010, **24**(1): 25 - 32.
[8] Dehlinger S, Leberre M, Benevent E, *et al*. Development of millimeter wave integrated circulator based on barium ferrite[J]. *Mater. Sci. Eng. C*, 2008, **27**(13): 755 - 758.
[9] Wang Y, Peng B, Zhang W L. Simulation of self-biased coplanar circulator using barium ferrite thin films [C]. In 2010 International Conference on Microwave and Millimeter Wave Technology, 2010: 543 - 546.
[10] Wang Y, Peng B, Zhang W L, et al. CPW Circulators with barium ferrite thin films[J] *J. Electronic Science and Technology*, 2010, **8**(4): 351 - 355.
[11] Bosma H. On stripline Y-junction at UHF [J]. *IEEE Trans. Micro. Theory Tech.*, 1964, **12**(1): 61 - 72.
[12] Fay C E, Comstock R. L. Operation of the ferrite junction circulator[J]. *IEEE Trans. Micro. Theory Tech.*, 1965, **13**(1): 15 - 27.