C-axis Oriented Polycrystalline BaFe12-xCoxO19 (x = 0, 0.3, 0.6, 0.9) for Millimeter Wave Self-biased Circulator at Ka Band

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Abstract. The anisotropic hexagonal magnetic material is prepared using conventional ceramic process. The high magnetic anisotropy field of hexagonal is essential to extend the device bandwidth for circulator operating at millimeter wave band. The modified hexagonal $BaFe_{12-x}Co_xO_{19}$ with about 9 kOe anisotropy field and its Electromagnetic property are presented. And a simulation certificating the circulator at Ka-band is given at the end of the paper.

Keywords: Hexaferrite; Circulator; Millimeter Microwave Device; Full-duplex.

1. Introduction

The idea of utilizing hexaferrite for ferrite devices at high frequency has been suggested for a very long time [1]. But the magnetic loss induced by high magnetic anisotropy hinders its application in practical scenarios. In this article, we present a modified hexaferrite used for wide-band mm-wave circulator. The cobalt ion is used to adjust the magnetic anisotropy field from 17 KOe to 10 KOe. The large anisotropy is not only benefit to shift the operation frequency toward high frequency but also to extend operation bandwidth [2]. But the original magnetic anisotropy for M-type hexaferrite is about 17 KOe, it is too large for the device working at Ka band. The cobalt ion substitution is successful in altering the magnetic anisotropy field while maintaining the high saturation magnetization. And oriented polycrystalline with micron crystal grain size is prepared to obtain low loss, high density, and self-bias property. The magnetic loss, magnetic remanence and saturation magnetization are properties that highly related to the microstructure of the ceramic. Finally, we present the device performance by Finite element simulation. The circulator with hexaferrite we papered has a large bandwidth of 6 GHz at Ka band.

2. Experimental Procedure

Oriented polycrystalline $BaFe_{12-x}Co_xO_{19}$ (x=0, 0.3, 0.6, 0.9) is presented using the conventional ceramic method. The raw materials $BaCO_3$, Fe_2O_3, and Co_3O_4 are weighted according to the stoichiometric ratio and well mixed. The mixed powder is calcined for 20 hours at 1300 °C. The long period of first calcined renders the raw material completely forms the magnetic phase. The magnetic particles are pressed densely in the presence of a strong external magnetic field. This pressed method can render the material magnetically aligned [3]. Before the press under the magnetic field, a 24 hours ball milling with deionized water is applied to crash the ceramic bulk into small particles. The crashed particles should be below the single domain size. Small particles along with 30% deionized water will rotate under the external magnetic field during the compacting. And then the oriented polycrystalline is sintered at 1250 °C for 2 hours to densify microstructure and eliminate pore.

The Phase composition was confirmed by X-ray diffraction (XRD, Rigaku, Minflex 600) with a Cu Kα radiation source (λ=0.154056 nm). The textured microstructure was identified by scanning electron microscope (SEM, Zeiss, Gemini 300). The magnetic performance was measured by system-vibrating sample magnetometer (VSM, lakeshore, 7404). And the magnetic loss ΔH was measured with a coplanar waveguide system equipped with a VNA. The measured property parameters were used to simulate a Ka band circulator based on the finite element method with the software Ansys HFSS.

3. Result and Discussion

3.1 Crystal Structure

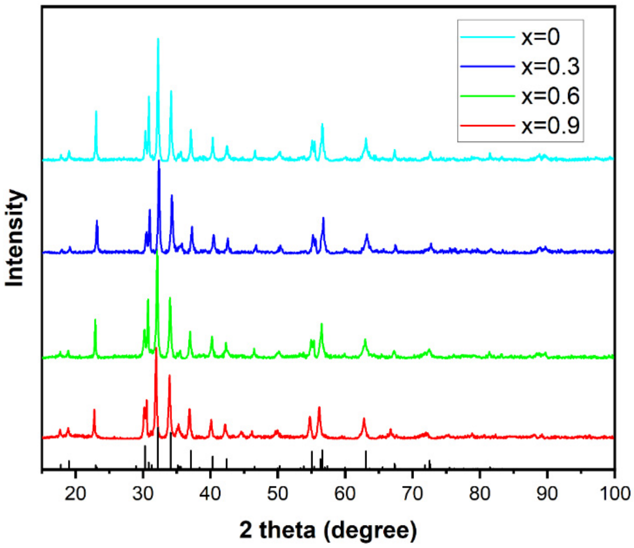

Fig 1. The X-ray diffraction patterns for $BaFe_{12-x}Co_xO_{19}$ (x=0, 0.3, 0.6, 0.9)

The XRD experimental data are presented in Fig.1. The powder used for measurement is so-called first milled powder. Unlike the normal conventional ceramic procedure, we use only one step to finish the whole new crystal phase formation procedure. The calcined powder forms the hexaferrite crystal structure completely after the one step Calcination. Attribute to the one step Calcination, the sample is not fully densified, so the desired size distribution of particles can be achieved more easily by ball milling. An appropriate ball milling process should be applied to guarantee the size distribution of milled particles. The particles are aligned and pressed under a uniaxially pressure of 10 MPa. Besides the particle size distribution, the fully crystallized magnetic phase is another critical factor to get a well orientated green body. The powder after first milling and before the press is measured with XRD to confirm the crystal structure. The standard diffraction peaks of M-type hexaferrite with space group $P6_3/mmc$ under the Fig.1 are provided from the standard diffraction card (#27-1029). All peaks for four sample accord with the standard diffraction card, no additional impurity phase has been detected. We can conclude from Fig.1 that all raw material has been fully transformed into M-type hexaferrite after 20 hours of 1300°C calcination.

3.2 Microstructure

Fig.2 shows the SEM patterns of the sintered sample. The pressed oriented sample is sintered for 2 hours at 1250°C to get a dense and uniform microstructure. And the small grain size is also needed for acquiring high magnetic remanence [4]. All four samples present strong oriented textured phase microstructure. According to both the cross-section view and surface view of the grain, the grains present like thin flat tablet. The thickness is controlled about 1μm which is within the single domain size. The small size of grain contributes to the high magnetic remanence, which will be confirmed in the next section. The difference of microstructure among the four chemical compositions is very slight. With the higher content of cobalt, some grain shows abnormal growth, large nonuniform grain starts to appear, and the grain boundary becomes rounded and obscure. All those evidences suggest that the cobalt ion can lower the temperature demand of sintering. For the sample with higher content of cobalt, the sintering temperature should shift a little lowlier to maintain the crystal microstructure.

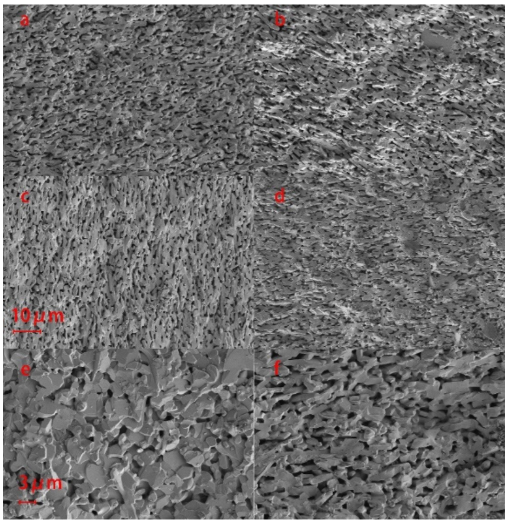

Fig 2. The SEM patterns for oriented textured $BaFe_{12-x}Co_xO_{19}$, a: x=0, b: x=0.3, c: x=0.6, d: x=0.9, e: surface view of x=0, f: cross-section view of x=0

Fig.2 e and f show the different view directions of one sample. We break the sample along the magnetic easy axis which is also the direction of the external magnetic field we applied when the sample is pressed. From the cross-section view, the grain looks like long bricks and lies aligned. And from this view the thickness of thin flat tablet is also easy to recognize. As contrast, the surface view of the sample shows no alignment and we can hardly see the thickness of the flat tablet. Those two different directions of view also give strong evidence of the crystal texture and alignment.

3.3 Magnetic Property

Fig.3 show the hysteresis loop of four different samples. And the magnetic parameter is listed in table 1. With the increasing amount of cobalt, the effective magneto-crystalline anisotropy field Ha decrease. This is the key effect and also our goal of substitution [2]. The value of Ha is driven from the hysteresis loop using the law of approach to saturation [5]. The following equations are used to get the value.

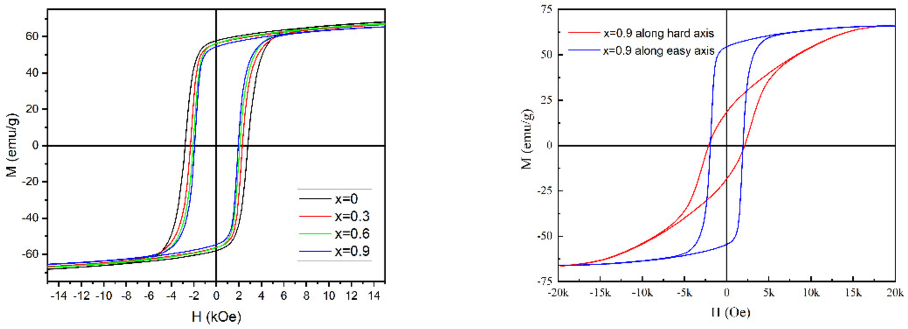

Fig 3. The hysteresis loop of sintered sample, the right-side picture shows the hysteresis loop along different magnetic axis

$$\mathrm{M} = M_s\left[1-\frac{a}{H}-\frac{b}{H^2}-\cdots\right]+\chi_p H \tag{1}$$

$$\mathrm{b} = \frac{4}{15}\frac{{K_u}^2}{{\mu_0}^2{M_s}^2} \tag{2}$$

$$H_a = \frac{2K_u}{\mu_0 M_s} \tag{3}$$

The decrease of Ha also contributes to the decrease of coercivity. More importantly, decreased Ha has a good advantage on boarding the operation bandwidth at Ka band circulator. Cobalt substitution has a negative influence on magnetic saturation. The reduction of magnetic saturation is not favorable, but the magnitude of reduction is relatively acceptable. As has been mentioned, the microstructure difference among the four samples is small, the four samples all present a strong alignment structure. The easy axis of all crystal grains is parallel to each other. So, all samples present high magnetic remanence. The crystal anisotropy can also be confirmed from the right-side picture of Fig.3. The hysteresis loop behaves differently along different crystal axis due to the magnetic crystal anisotropy.

Table 1. The magnetic parameter of four different samples

x	Ms (emu/g)	Hc (Oe)	Ha (Oe)	Mr/Ms
x=0	68	2790	17k	85%
x=0.3	67.9	2305	14k	84%
x=0.6	67.6	2073	11k	83%
x=0.9	65.8	1932	10k	83%

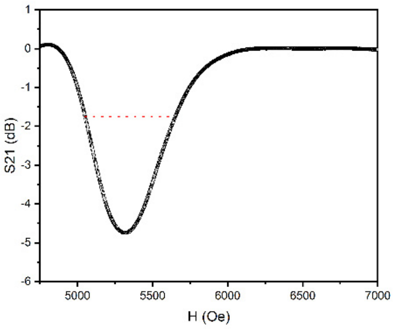

Fig 4. The ferromagnetic resonance linewidth ΔH of $BaFe_{11.1}Co_{0.9}O_{19}$

Due to the existing of Ha, the relationship between ferromagnetic resonance and applied is not follow the kittle equation:

$$\omega_0 = \gamma\{[H_z + (N_y - N_z)M_z] \times [H_z + (N_x - N_z)M_z]\}^{1/2} \tag{4}$$

The anisotropy field provides an additional frequency. That lead ferrite with high anisotropy occur ferromagnetic resonance at higher frequency. In Fig.4 the sample is placed above a coplanar waveguide, and the S21 magnitude of 34 GHz is recorded. The gap between two half power points gives ΔH 604 Oe. It is a disadvantage that M-type hexaferrite have a such large magnetic loss compared to other microwave ferrites like YIG. But the higher resonance frequency is in favor of high frequency devices.

3.4 Circulator Device Performance

The wide band circulator design is based on the continuous tracking principle [6]. The theory tells the circulator will work when $0.5<|\frac{\kappa}{\mu}|<1$. For a circulator operating between 7~12.4 GHz. The optimal material is ferrite with 2150 Gauss and zero anisotropy. But for a higher frequency, we need larger saturation magnetization or larger anisotropy. Since the saturation magnetization of hexaferrite is limited under 4500 Gauss, the hexaferrite with large anisotropy is suitable for Ka band.

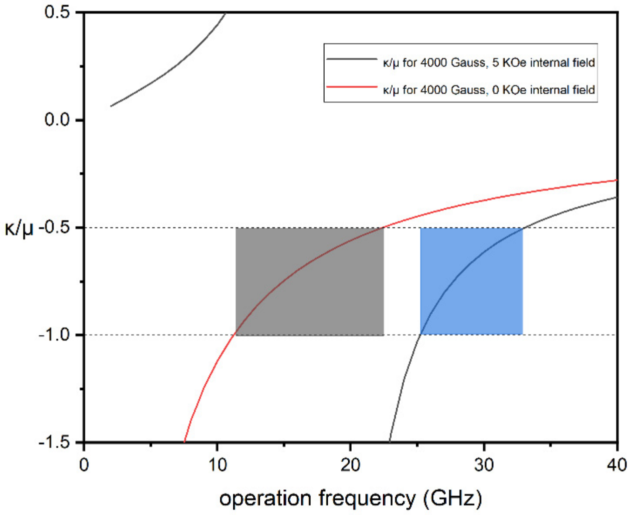

Fig 5. The value of $\frac{\kappa}{\mu}$ for ferrite with different biased field

As we can conclude for Fig.5, the large anisotropy can shift the operation band towards high frequency despite the two ferrites having the same saturation magnetization. To verify the device, we use the finite element method to simulate the performance of circulator. The continuous tracking principle has been applied to achieve wide-band performance. The performance of circulator as well as the design model is presented in Fig.6. A board band performance of isolation greater than -20 dB occurs at 28~34 GHz. And obtain a total 6 GHz bandwidth with an insertion loss less than -0.9 dB. The continuous tracking principle can achieve octave bandwidth, but since we use large anisotropy instead of large saturation magnetization, the bandwidth cannot achieve octave bandwidth. This can also be understood from Fig.5 that high anisotropy does shift the operation band towards the higher frequency, but the range of $0.5<|\frac{\kappa}{\mu}|<1$ shrinks.

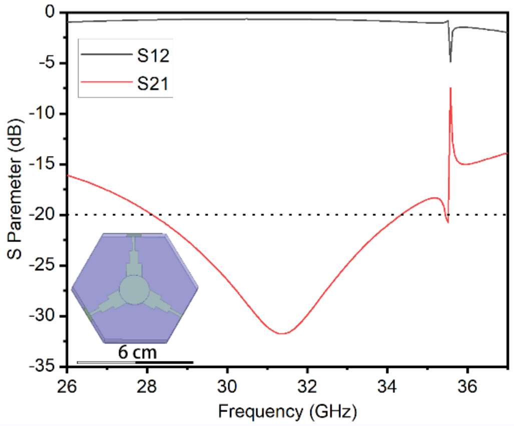

Fig 6. The performance of circulator at Ka band and its model at the bottom of left

4. Summary

The oriented hexaferrite $BaFe_{12-x}Co_xO_{19}$ (x = 0, 0.3, 0.6, 0.9) has been successfully made. All samples present high magnetic remanence. With the substitution of cobalt ion for iron ion the anisotropy field decreased from 17kOe to 10kOe. The modified anisotropy field is more suitable for the circulator at Ka band. Finally, we presented the simulation of the self-bias circulator using $BaFe_{11.1}Co_{0.9}O_{19}$. The circulator has isolation greater than -20 dB and insertion loss less than -0.9 dB from 28~34 GHz.

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