

Millimetre-wave isolator based on Al substituted Ba ferrite

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Abstract. A mm-wave isolator is fabricated and studied. The operating frequency of the devices is 78.5 GHz. A bandwidth at the level of -3 dB equals 1.6 GHz. The device used a flux grown single-crystal aluminum substituted barium ferrite.

1. Introduction

During the past two decades or so the an increase in operating frequencies provides great advantages for the radar and communication systems. One of the approaches to increase frequency of ferrite devices is to use ferrite materials with large magnetocrystalline anisotropy. Magnetic properties of ferrite materials can be widely tuned by substitution. Modification of barium hexaferrite ($\text{BaFe}_{12}\text{O}_{19}$) by substitution of iron atoms gives significant changes in physical and chemical characteristics such as magnetocrystalline anisotropy, coercive force or Curie temperature [1-17]. Hexagonal ferrites with large magnetocrystalline anisotropy are promising for mm-wave applications as well as for use in sub-terahertz range. In particular, tunable resonators [17-21], isolators [22] and radio-absorbing coatings [13] were developed with the use of films or bulk hexaferrite materials. In this context the elaboration of a robust technology for production of hexaferrite single crystals became important in recent years [23-25].

Purpose of the present work is to grow the aluminum substituted barium ferrite with flux technique and to demonstrate its possible application for mm-wave isolators.

2. Experimental details

Iron oxide ($\gamma\text{-Fe}_2\text{O}_3$, 99.9 %), aluminum oxide ($\gamma\text{-Al}_2\text{O}_3$), barium carbonate (BaCO_3) and sodium carbonate (Na_2CO_3) were used for crystal growth [16]. The resistive furnace construction used for single crystal growth was earlier described elsewhere [26]. We used the following composition of initial batch for ferrite crystal growth: Al_2O_3 – 15.63 wt.%, Fe_2O_3 – 51.13 wt.%, BaCO_3 – 18.00 wt.%, Na_2CO_3 – 24.75 wt.%.



The raw materials were ground in an agate mortar and set into a platinum crucible. The crucible was placed in a resistance furnace equipped with a type S thermocouple. To homogenize the melt, the furnace was maintained at 1260 °C for 3 h followed by cooling at a rate of 4.5 K/h to 900 °C. After that the system was naturally cooled to room temperature. The spontaneously obtained crystals with a size of up to 8 mm were separated from the solidified melt by leaching in hot nitric acid to remove side phases (e.g. NaFeO₂).

Using carbonate flux technique high-quality Al substituted Ba-ferrite crystals of composition BaFe_{12-x}Al_xO₁₉ with $x = 0.5$ were grown. Applying the flux technique the crystal growth temperature can be reduced to below 1300 °C, compared with much higher temperatures necessary for flux free crystal growth methods [27, 28]. Fig. 1 presents crystals with edge-length up to 6 mm and the typical shape obtained in our study.



Figure 1. Photograph of BaFe_{12-x}Al_xO₁₉ single crystals obtained from flux with mm-scale. One segment of the ruler corresponds to one millimetre.

Using the grown single crystals we made mm-wave waveguide isolator by conventional way [29]. The single crystals were split into narrow slabs. Typical thickness of the slabs was about 100 µm. In-plane sizes of the slabs were of approximately 2 mm². The easy axis of the crystal magnetization (c-axis) was orientated perpendicular to the slab plane. To produce an isolator a sample was positioned inside the WR-10 waveguide section on the narrow wall as shown in Fig. 2. The vector network analyzer Rohde&Schwarz ZVA40 with millimeter-wave converters ZVA-Z110 was used. Measurements of S-parameters were carried out for forward and backward propagation direction of test electromagnetic signal through the waveguide section. A part of the measurement cell containing the magnetic sample was magnetized with uniform magnetic field directed perpendicular to the sample plane. The bias field was varied in the range of 0-6 kOe.

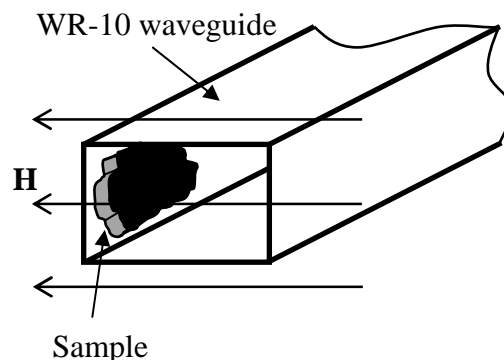


Figure 2. Schematic view of the isolator with magnetic hexaferrite sample.

3. Results and discussion

In accordance with magnetic characterization and previously reported data [16-17], the ferromagnetic resonance frequency for the $\text{BaAl}_{0.5}\text{Fe}_{11.5}\text{O}_{19}$ is in the range of 50-70 GHz for external magnetic fields of $H = 0-6$ kOe. Therefore, electromagnetic resonances only were observed in range of 75-100 GHz. Fig. 3 shows typical insertion losses in forward and backward direction, i.e. $S_{21}(f)$ and $S_{12}(f)$ characteristics, respectively. The electromagnetic resonances were observed at frequencies of about 78.6 GHz and 96.3 GHz. The measurement device demonstrated reciprocity of the characteristics in zero magnetic field (Fig. 3(a)). The resonance absorption is very similar in both directions of the electromagnetic wave propagation. Application of the bias magnetic field resulted in a non-reciprocal propagation of the test electromagnetic signals in forward and backward directions typical for resonant isolators based on ferrite loaded waveguides (see Fig. 3(b)).

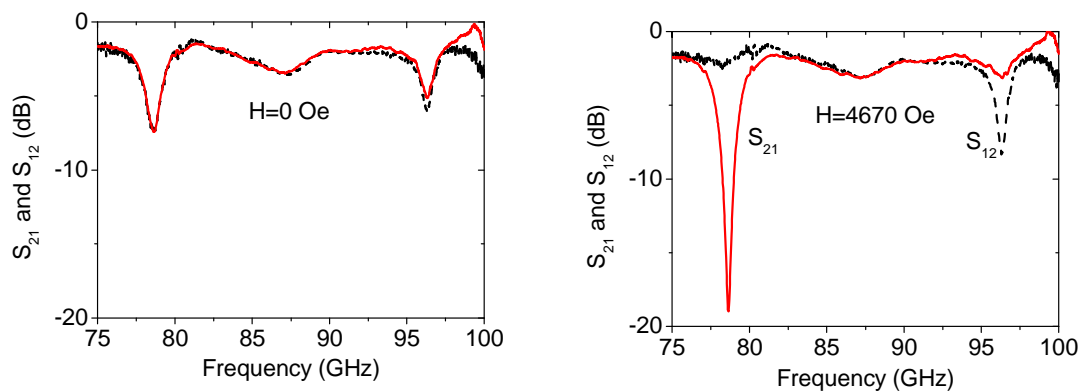


Figure 3. Typical $S_{21}(f)$ and $S_{12}(f)$ characteristics measured for zero magnetic field (left) and for $H = 4670$ Oe (right).

Considering the resonant peak observed at the frequency of 78.6 GHz it should be noted that for $H=0$ Oe the resonant frequency f_{res} was 78.743 GHz. An increase of H up to 2820 Oe led to complete diminishing of resonant absorption in backward direction (see $S_{12}(f)$ characteristic) and to the highest absorption in forward direction (see $S_{21}(f)$ characteristic). The resonant frequency of the peak on $S_{21}(f)$ characteristic was slightly decreased down to 78.274 GHz. Further increase of H up to 3265 Oe caused no visible changes in the characteristics. For fields exceeding 3265 Oe an increase of H leads to an increase in f_{res} and the value of the resonance absorption depth is reduced. The results obtained from the measurements of $S_{21}(f)$ and $S_{21}(f)$ characteristics are summarized in Fig. 4.

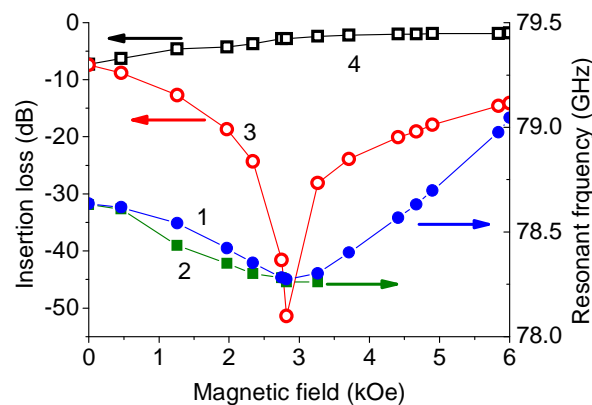


Figure 4. Resonance frequency for S_{21} (curve 1) and S_{12} (curve 2) and insertion loss at the resonance frequency for S_{21} (curve 3) and S_{12} (curve 4) as a function of bias magnetic field.

It is well known that the ferromagnetic resonance is coupled with some electromagnetic modes. Considering this coupling one can conclude that the value of magnetic field H_S for which f_{res} begins to increase corresponds to the transition of the magnetic sample to the saturation state. From this point of view the saturation magnetization $4\pi M_S$ of the investigated $\text{BaAl}_{0.5}\text{Fe}_{11.5}\text{O}_{19}$ hexaferrite can be estimated as $4\pi M_S = H_S = 3265$ G. This value obtained from the microwave measurements is reasonably close to that measured with the SQUID magnetometer (see the Fig. 5).

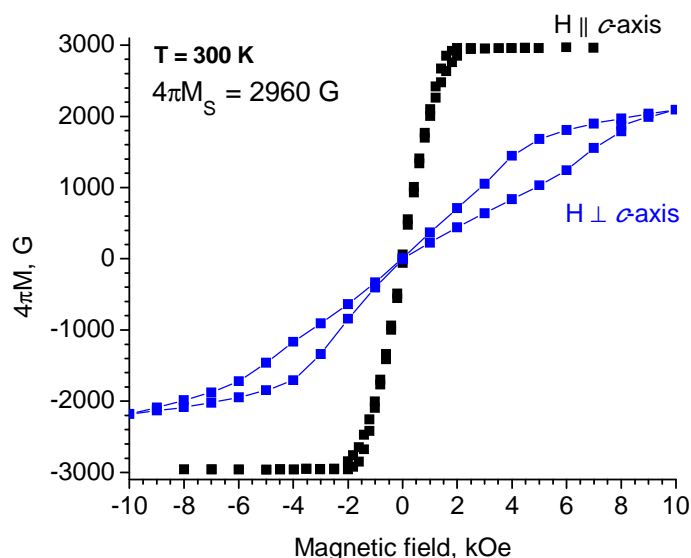


Figure 5. Magnetization as a function of magnetic field at $T = 300$ K.

The absorption curve (Fig. 3) has a shape close to a Lorentzian profile. The resulting Q-factor of 47 is typical for dielectric modes in the W-band [19, 20]. The obtained characteristics indicate that the single crystals grown by flux technique have good quality and can be used for the development of another millimeter-wave devices. Among them are magnetic field controllable attenuators or notch filters. The operating frequency of the devices would be around 78.5 GHz. A bandwidth at the level of -3 dB from minimum value of the insertion loss equals 1.6 GHz.

4. Conclusions

A mm-wave isolator is fabricated and studied. The operating frequency of the device is 78.5 GHz. A bandwidth at the level of -3 dB from minimum value of the insertion loss equals 1.6 GHz. The use of hexagonal ferrites having a large uniaxial magnetocrystalline anisotropy is a powerful tool to increase significantly an operating frequency of mm-wave devices.

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