Self-biased planar millimeter wave notch filters based on magnetostatic wave excitation in barium hexagonal ferrite thin films

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The use of M-type barium hexagonal ferrite (BaM) thin films for self-biased planar millimeter wave notch filters was demonstrated for the first time. The BaM film was grown by pulsed laser deposition and showed a remanent to saturation magnetization ratio of 0.99 and a 60 GHz ferromagnetic resonance linewidth of about 300 Oe. The filter consisted of a BaM film element positioned on the top of a coplanar waveguide and showed a band-stop response at 53 GHz for zero external fields. This filtering response resulted from power absorption due to magnetostatic wave excitation in the BaM film. © 2010 American Institute of Physics. [doi:10.1063/1.3504256]

Magnetic garnet materials such as yttrium iron garnet (YIG) have been widely used as active components in many microwave devices. These devices include YIG resonators, filters, circulators, and phase shifters. They have had a major impact on the advancement of microwave technology. The underlying effects in those devices include ferromagnetic resonance (FMR), Faraday rotation, field displacement, and magnetostatic wave (MSW) propagation. Whatever the basis for a given device, the operation frequency is determined essentially by the FMR frequency of the garnet material. The magnetic garnets are low-magnetization low-anisotropy materials and, therefore, typically have a low FMR frequency ($f_{\text{FMR}}$) in the gigahertz range. This imposes an upper limit on the operation frequency of compact YIG-based devices in the 10–18 GHz range.

Presently, there is a critical need for the extension of current garnet-based microwave devices into the millimeter (mm) wave regime. In principle, this frequency extension can be realized through the use of very high external magnetic bias fields ($H$). In practice, however, the use of high external fields is usually impractical because of the increased device size and weight as well as incompatibility with monolithic integrated circuit technology.

To meet this need, one strategy is to use hexagonal ferrite thin films, such as M-type barium hexagonal ferrite BaFe$_2$O$_{19}$ (BaM) thin films, as a replacement for those cubic garnets. Hexagonal ferrite films can have high magnetocrystalline anisotropy fields ($H_a$). This high internal field can facilitate FMR and hence device operation at mm-wave frequencies. The films can also have high remanence ($M_r$) that can allow for device operation in absence of external magnetic fields, namely, self bias operation, as well as operation frequency tuning with low external fields.

Recently, progress has been made in the demonstration, both numerical and experimental, of the use of BaM thin films with small FMR linewidths to fabricate planar mm-wave notch filters and phase shifters. Note that small linewidths are essential to the realization of low-loss devices. Those filters and phase shifters, however, are not self biased. This is because the BaM films used in those devices had their $c$ axes normal to the film planes. Such $c$ axis orientation gave rise to a near unity demagnetizing factor along the film normal direction and a corresponding small $M_r$ value.

Yoon et al. were able to use pulsed laser deposition (PLD) to grow in-plane $c$-axis oriented BaM films with higher remanence, at a remanent ($M_r$) to saturation magnetization ($M_s$) ratio of 0.94. Those “in-plane” films, however, had very broad FMR peaks, with a 50–60 GHz peak-to-peak derivative linewidth $\Delta H$ of 1150 Oe or larger. Note that the high $M_r/M_s$ ratios in those films derived from the near zero demagnetizing factor along the $c$ axis. Song et al. reported in-plane BaM films with slightly lower $M_r/M_s$ ratios at about 0.84 but with much narrower linewidths of about 250 Oe. Those films, however, were made through a hybrid process that involved both PLD and liquid phase epitaxy along with postdeposition surface flux cleaning.

This paper reports a new self-biased planar mm-wave notch filter that made use of MSW excitation in an in-plane $c$-axis oriented BaM thin film. The BaM film was grown by PLD and showed an anisotropy field that matches the value of BaM crystals, a $M_r/M_s$ ratio that is higher than previous BaM films, and a $\Delta H$ value that is a factor of four smaller than those of previous PLD films. The device consisted of a BaM film on the top of a coplanar waveguide (CPW). The alternating magnetic field produced by the CPW was spatially nonuniform. This nonuniform field gave rise to the excitation of MSWs in the film. Such MSW excitation led to a power absorption in a certain frequency range, and the net effect is the band-stop filtering response of the device.

It is important to emphasize that the BaM notch filter presented here differs significantly from the devices in previous work. (1) The underlying effects are different. The filter in this work relied on MSW excitation in the film, while the filters and phase shifters in previous work used FMR effects. (2) The filter in this work was self biased, while previous devices were not. This self bias operation derived critically from the use of a high-$M_r$ film. (3) The frequency tuning in this work was done with low fields, while the tuning in previous work required much higher fields.

It is also important to emphasize that this work demonstrates the feasibility of basic PLD growth of BaM thin films with high suitability for device applications. The films were grown on an $a$-plane sapphire substrate, as in Refs. 8 and 9. The high quality was realized through several changes in the substrate temperature during the deposition, along with the optimization of other deposition parameters. The sequential changes in temperature resulted in a series of BaM layers...
with slightly different structure properties. This quasimulti-layered configuration served to release interfacial strain and thereby realize high-quality films.

The films were deposited on 0.5 mm thick sapphire substrates. The crystallographic $m$ planes of the BaM structure formed on the $a$ planes of the sapphire. To a large extent, the film quality depends on deposition control parameters and postdeposition annealing conditions.\textsuperscript{10} Deposition parameters were optimized for films with a thickness of several microns and with both high $M_s/M_a$ ratios and small $\Delta H$ values. The optimized parameters were listed below. (1) The energy fluence of the laser beam was set to 0.8 J/cm$^2$. (2) The repetition rate of the laser pulses was 40 Hz. (3) The target-to-substrate distance was set to 6.0 cm. (4) During the deposition, the substrate temperature was varied as follows: (i) 700 °C for 3 min, (ii) 800 °C for 60 min, (iii) 700 °C for 60 min, and (iv) 800 °C for 20 min. (5) The entire process was done in high-purity (99.999%) oxygen at a pressure of 100 mTorr. (6) After the deposition, the film was annealed at 1000 °C in high-purity oxygen for 4 h.

Although the control parameters given above were all critical, the temperature change during the deposition played an essential role in the realization of films with high remanence and low loss. The reasoning behind the four-step temperature control sequence is straightforward. The first low-temperature short-deposition time step yields a very thin somewhat degraded BaM layer. This thin layer then serves as a buffer for the release of strain in the second higher temperature layer. This strain normally arises from the large mismatch of the $c$-axis length between the BaM and the sapphire. Note that the mismatch of the $c$-axis length between the BaM and the substrate. Note that the mismatch of the $c$-axis length between the BaM and the sapphire is very large, about 12%. The second layer is expected to be of higher quality as it is deposited at a high temperature. There might still exist, however, vertical threading dislocations in this layer due to the large lattice mismatch. The deposition of the third layer at a reduced temperature will then serve to reduce the density of the threading dislocation. As with layer two, the top layer is then deposited at a higher temperature and is expected to be of high quality. This high-quality cap layer, in turn, can serve to promote a higher quality in layer three during the postdeposition annealing.

Figure 1 gives the x-ray diffraction (XRD) data of a BaM film. Graph (a) shows an XRD profile, and graph (b) shows an XRD rocking curve. The profile in (a) shows three strong peaks. The central peak comes from the sapphire and the other two are from the $m$ planes of the BaM film. There are no peaks for other planes of the BaM film or the sapphire, or for other phases. The rocking curve for the M(200) peak in (b) shows a “full width at half maximum” (FWHM) of 0.85°. This value is very small and indicates a very small deviation of the $c$-axis orientation over the film. Note that this FWHM value is about 10% lower than that reported in Ref. 9. These results clearly indicate that the film has a $c$-axis that is in the film plan and is highly oriented.

Figure 2 shows two scanning electron microscopy (SEM) images. The one in (a) is for the film surface. The one in (b) is for the cross section of the film. The image in (a) shows a reasonably smooth surface and no notable holes. It also shows many fine lines that correspond to fine parallel cracks along the direction perpendicular to the $c$ axis. The parallelism of these cracks gives a rough measure of the good orientation of the $c$ axis. The image in (b) shows that the film thickness is uniform at 2.52 μm and there are no cracks at the film-substrate interface.

Figure 3 shows two magnetic induction ($4\pi M$) versus field ($H$) hysteresis loops measured by vibrating sample magnetometer (VSM) methods along the in-plane easy and hard axes, as indicated. The easy axis is along the $c$ axis defined by the XRD measurements. The dashed lines indicate the extrapolations used to determine the anisotropy field $H_a$. Three results are evident. (1) The film has an extremely well defined in-plane uniaxial anisotropy with the easy axis along the $c$ axis. (2) The data indicate a $H_a$ value of about 16.9 kOe, a $4\pi M_s$ value of about 3.9 kG, and an easy-axis coercive force of about 200 Oe. These values are close to those for high-quality BaM films reported previously.\textsuperscript{9,10} (3) The film has an $M_s/M_a$ ratio of 0.99, which is very close to unity and is the highest value ever obtained for BaM films. These results clearly confirm the in-plane orientation of the $c$ axis and demonstrate the near ideal in-plane uniaxial anisotropy for this film.

Figure 4 gives FMR data measured with a V-band shorted waveguide. Graph (a) shows three FMR derivative absorption profiles at different frequencies. The circles show the data. The curves show fits to a Lorentzian derivative trial

![Image](https://via.placeholder.com/150)
For the data in (a) shows a band-stop response in the frequency range which corresponds to the MSW bandwidth.

due to the FMR effect. Note that the linewidth \( \Delta f \) was estimated with \( \Delta f = \frac{(df_{\text{FMR}}/dH)(3^{1/2}\Delta H)}{H_0} \) at \( H = 0 \) and \( \Delta H = 300 \) Oe. These results represent the first demonstration of a self-biased compact BaM filter. The data in (c) indicate that the filter can be tuned for higher frequency operations with relatively low fields.

The results presented above clearly demonstrate the feasibility of the basic PLD growth of BaM films with both high remanence and low loss and the use of such films for self-biased planar mm-wave devices. Work is underway that will use MSW resonances in narrow BaM film strips to make BaM notch filters with much higher absorption and narrower bandwidths and use two BaM film elements with different \( H_a \) values to realize BaM bandpass filters. Future work on the development of BaM films with even higher anisotropy fields and the use of these films for self-biased devices with even higher frequencies is also of great interest. This can be realized, for example, through Al doping in BaM films.

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