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Magnetically Tunable Microwave Filters based on YBCO/YIG/GGG Heterostructures

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Abstract. Superconducting, monolithic magnetically tunable microwave filters have been designed and fabricated demonstrating high tuning ranges (up to 19%) at a center frequency of 10 GHz. These filters are based on fully epitaxial $YBa_2Cu_3O_7$ (YBCO) thin films grown by pulsed laser deposition onto liquid-phase epitaxy yttrium iron garnet (YIG) layers on gadolinium iron garnet (GGG) substrates. Mechanisms resulting in variations of the bandwidth and insertion losses upon tuning are analyzed and understood in terms of the material properties of YIG and GGG.

Keywords: high temperature superconductor, microwave filter, magnetically tunable, yttrium iron garnet, pulsed laser deposition

1. Introduction

The ability to tune high temperature superconducting (HTS) filters over a wide frequency range has been identified as an important step in enhancing the applicability of superconducting circuits to a wide range of communications and radar systems [1,2]. Tunable microwave devices, such as filters [3–6], mixers, phase shifters [7,8] and delay lines, even with limited tunabilities have significant importance in microwave communications and could enhance the performance of subsystems in addition to increasing the designer's freedom in configuring innovative circuitry. In many applications, it is often necessary to tune the electrical characteristics of the circuitry after the circuit has been manufactured, especially for high performance devices such as high-Q resonators and multi-pole narrow band filters. Tuning is predominantly achieved by mechanical means, which is often slow. Electronic tuning using varactor diode elements in MIC structures suffers from high pass-band insertion losses. Alternatively, the field-dependence of the permittivity of certain dielectrics, such as ferroelectrics, can be exploited to this purpose [4–7]. Current state-of-the-art filters of this kind suffer from relatively high insertion losses (typically 10 dB for three-pole filters) resulting from inherent losses in the tunable dielectric, and from minute variations in a very critical device geometry.

It is anticipated that the difficulties encountered in the case of electrically and mechanically tunable microwave filters can be overcome by the use of an active magnetic material, such as yttrium iron garnet (YIG). Tuning is achieved by varying this material's magnetic permeability by the application of a magnetic field. In the present work, this magnetic tuning is combined with HTS thin film technology, which has shown to result in very high-Q devices at significantly lower device volumes and weights than feasible with conventional metals [9,10].

The current work requires high-quality $YBa_2Cu_3O_{7-\delta}$ films to be integrated with yttrium iron garnet (YIG). YIG crystals are available only in small sample sizes and at prohibitive cost. Therefore, commercially available, liquid-phase epitaxy grown YIG films on gadolinium gallium garnet (GGG) substrates were used. YBCO was deposited by pulsed laser deposition (PLD) using a buffer layer scheme developed earlier [11].

2. Filter Design

The present study compares two micro-strip geometry filter types: inter-digital and parallel coupled-line. Figure 1 compares the three structures. Both designs are relatively compact, with the inter-digital design resulting in the smaller device.

Design calculations and simulations using SONNET® were based on the assumption that the permeability tensor of YIG can be approximated by a simple scalar μ, changing from 0.92 to 0.4 upon application of a magnetic field of approximately 2 kGauss. The parameters used in the simulations are shown in Table 1. Filters were designed for a center frequency $f_0 = 10\,\mathrm{GHz}$, and a bandwidth of 100 MHz.

Simulations for the inter-digital design predict a tuning range of 11%, accompanied by an increase of the 3-dB bandwidth of approximately 38% and an increase of the insertion loss from 4.6 dB to 5.6 dB (assuming a copper signal line). Considering that the model considers all materials losses as constants, the increase in insertion loss and bandwidth can only be attributed to a change in the coupling from the connecting waveguide to the resonators and between the individual resonators.

The same is true for the parallel-coupled design. Here, the tuning range is 9.4%, the increase in the bandwidth 48%, and the insertion loss increases from 2.8 dB to 4 dB.

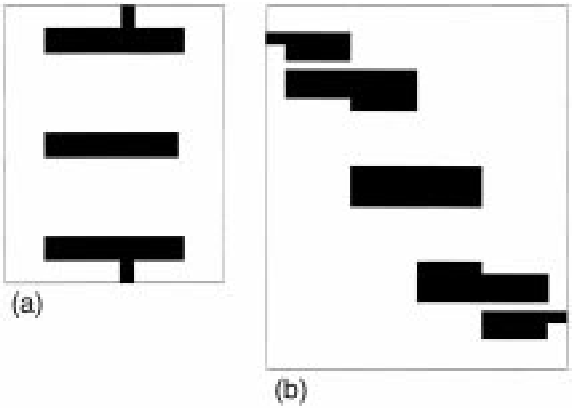

Fig. 1. Drawing of the two filter structures analyzed in this work. Figure is to scale. (a): Inter-digital (358 mils by 284 mils), (b): parallel coupled (464 mils by 420 mils).

Table 1. Parameters used in the design of the tunable filters

Material	Thickness	ε_{rel}	tan δ
YIG	4 mils	16	0.0005
GGG	20 mils	12	0.0001

3. Film Growth and Device Fabrication

Growth of epitaxial YBCO films directly onto YIG is not possible, both due to the lattice mismatch and chemical incompatibilities. In fact, care must be taken to avoid iron migration from the YIG into the YBCO. A patented double buffer layer scheme was developed by Neocera to that end. The buffer layers (200 Å of $SrZrO_3$ and 100 Å of $BaZrO_3$) and the 4000 Å YBCO film are PLD-grown at a substrate temperature of 780°C, an oxygen pressure of 220 millitorr, a laser energy density of 2 J/cm^2 at the target, and a laser pulse repetition-rate of 10 HZ. For comparison purposes and for room-temperature measurements, some devices were fabricated with a metal signal line rather than using YBCO. Gold films were deposited in vacuum (again using PLD), with an energy density of approximately 5 J/cm^2. The typical gold layer thickness is 2 μm.

AC susceptibility measurements on a YBCO film grown onto a YIG/GGG substrate using these buffer layers demonstrated the required high quality of the YBCO film ($T_c > 88\,\mathrm{K}, \Delta T_c < 0.4\,\mathrm{K}$).

Standard photolithographic techniques were used to pattern the devices. For the ground plane, about 2 μm of gold was deposited on the back side of the substrate. The finished filters were mounted in a copper package which was suspended in a bath of liquid nitrogen for cryogenic measurements. A magnetic field of up to 2 kGauss in the plane of the substrate was applied by an electromagnet, and measurements were performed using a Hewlett-Packard 8722D Vector Network Analyzer.

4. Results

Experimental results for an inter-digital gold test filter are shown in Fig. 2. A broad tuning range of 12% is

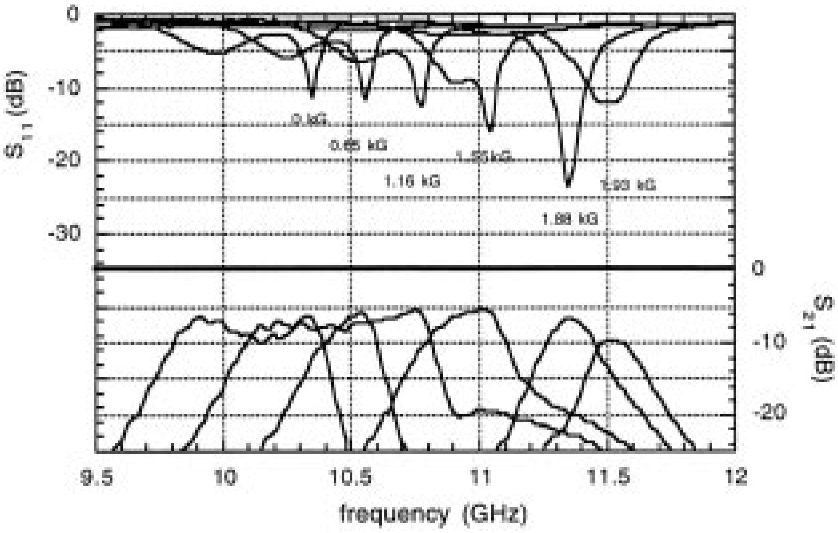

Fig. 2. Room-temperature frequency response (S_{11} and S_{21}) of an inter-digital Au/YIG/GGG filter at room temperature for different values of the applied magnetic field (given as parameter).

achieved at room temperature, and insertion losses are of the order of 5 dB. It is clearly observed that the individual poles of the device are out of band, resulting in an overall poor return loss (S_{11}). These poles appear to shift at a different rate, however, so that there exists a value of the magnetic field at which they coincide. At that value (approximately 1.9 kGauss), a return loss of nearly 25 dB is observed.

The same device was measured at 77 K, and its behavior was not distinguishable from that of the superconducting filter at the same temperature as shown in Fig. 3. An increase of the insertion loss is observed upon cooling, indicating that the dominating contribution comes from the YIG/GGG structure rather than the conducting layer. Again, it appears that the poles tune separately in this device, but the overall tuning range of 14% is satisfactory.

For devices in the parallel-coupled geometry, a

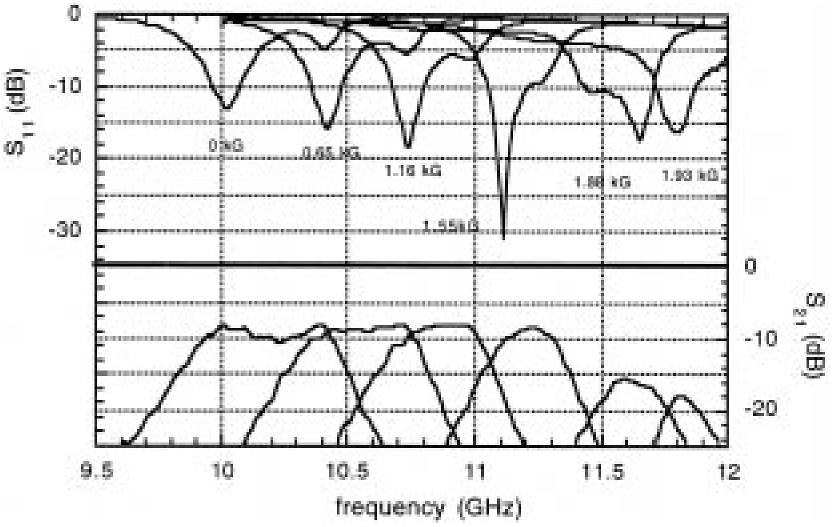

Fig. 3. Frequency response (S_{11} and S_{21}) at 77 K of an inter-digital YBCO/YIG/GGG for different values of the applied magnetic field (given as parameter).

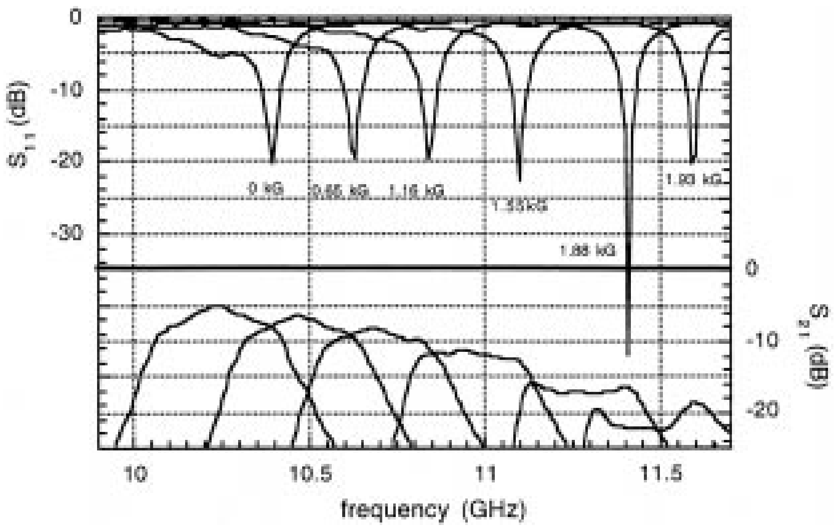

Fig. 4. Room-temperature frequency response (S_{11} and S_{21}) of a parallel-coupled Au/YIG/GGG filter at room temperature for different values of the applied magnetic field (given as parameter). A 11% tuning range is observed.

much smaller pole separation is observed. This is shown in Fig. 4 for a gold device measured at room temperature, which exhibits a tunability of about 11%. Again, cooling of the device to 77 K resulted in an increase of the insertion loss, with no significant difference between the gold and the YBCO filters observed. Results for the superconducting structure are shown in Fig. 5, demonstrating a 19% tunability.

To the best of the authors' knowledge, this device thus exhibits the highest tuning range ever reported for a monolithic magnetically-tuned filter and exhibits a performance superior to devices based on single-crystalline YIG-HTS hybrid devices [12] both with respect to tunability and insertion losses.

5. Discussion

The above results can be summarized by noting that large tunabilities have been observed, that the

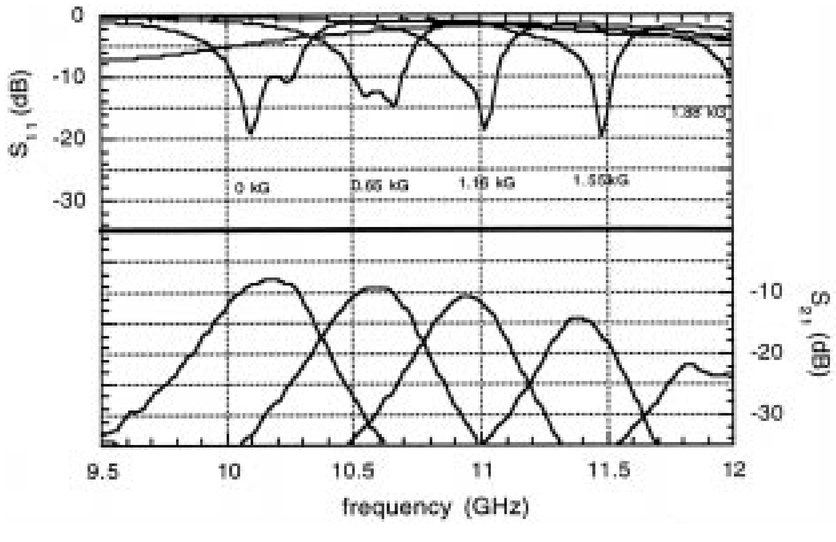

Fig. 5. Frequency response (S_{11} and S_{21}) at 77 K of a parallel-coupled YBCO/YIG/GGG for different values of the applied magnetic field (given as parameter). Note the large tuning range of 19%.

experimental data deviates clearly from the numerical simulations, and that the insertion losses increase upon cooling of the device.

The large differences between the simulated curves and the experimentally observed filter responses indicate that the assumptions used for the calculations were incorrect, in particular that the permeability can not be approximated by a scalar. In fact, not only are the components of the tensor significantly different from each other, they also exhibit a different field dependence. This is evidenced in the ''cross-over'' of the poles as observed most clearly in the interdigital design (Figs. 2 and 3). Therefore, when designing microwave devices based on single-crystalline YIG, a tensorial $\mu_{x,y,z}$ with components that have a different field-dependence must be considered [13].

Correction of the design to account for the tensorial nature of the permeability will also reduce the insertion loss of the devices. In addition to that, however, the strong increase of the losses with decreasing temperature indicates the significant contribution from the substrate. In fact, we have performed microwave dielectrometer measurements at 24 GHz on a blank GGG substrate, indicating that cooling from room temperature to 77 K increases its loss tangent by more than a factor of three to 0.002. It is noteworthy that miniature HTS circulators fabricated directly on IG single crystalline substrates have shown insertion losses of 0.23 dB at 10 GHz [10]. This points out the possibility of fabricating tunable filters with significantly lower losses than those observed in the present case by a proper choice of the substrate design, including thinning the GGG substrate.

The change of the bandwidth with tuning is largely due to the variations in the coupling between the resonators, resulting from the decrease of YIG's permeability. Note that the permeability changes globally with the applied field, therefore both in the areas that predominantly influence the resonance frequency as well as in the areas responsible for the coupling. The difference between the two types of filters investigated is thus clearly a consequence of the different geometries.

Removing the YIG between the resonators should, in principle, reduce the change of the bandwidth with tuning. This was attempted experimentally (using a hot phosphoric acid etch to remove the YIG); however, the associated decrease in the tunability was significant and precluded a determination of the merits of this approach.

6. Conclusions and Future Directions

We have demonstrated that monolithic magnetically tunable high-temperature superconducting filters can be fabricated with tunabilities as high as 19% (at 2 kGauss). To the best of the authors' knowledge, this value compares favorably to those published on devices based on YIG single crystals and is the first of this kind for monolithic devices.

The device performance of these filters is limited by an oversimplified assumption used in the design (namely, a scalar permeability) and by losses associated with the GGG substrate.

Further work will focus on the use of a thinner GGG substrate. In addition, a device-design based on the full permeability tensor will be considered. Alternatively, approaches based on polycrystalline (thus isotropic) YIG will be explored.

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