A systematic way to YIG-filter-design

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***Abstract*— YIG-filters are key components in microwave test and measurement instruments. Whereas their basic principles are well established, only few details about the design and realization of modern multi-octave filters have been published. Therefore, research and development to find a systematic and accurate way of calculating and reproducibly building modern YIG-filters has been initiated at Rohde & Schwarz. This enables us to obtain a profound understanding and control of parameters and overcome empirical methods of manual rework.**

I. Introduction

YIG-filters are magnetically tunable filters with resonators made of single crystal YIG (Yttrium-Iron-Garnet) spheres. They provide multi-octave tuning ranges up to 50 GHz.

In front-ends of microwave test and measurement instruments such as spectrum analyzers, YIG-bandpass-filters preceding the first mixer are essential to suppress undesired signals, in particular those at the mirror frequency.

To Rohde & Schwarz as one of the leading manufacturers of microwave test and measurement equipment, the YIG-technology is of fundamental importance. In order to optimize the use of YIG filters in our instruments, we need a full understanding and control of all filter parameters. However, many conventional ways of YIG-filter-design and development are based on grown experiences or trial-and-error methods. We therefore started a research project with the aim of a full understanding of design principles and control over all parameters. This includes the crystal growth of YIG and manufacturing of high quality spheres as well as the reproducible and precise assembly of all filter mechanics. Contrary to other YIG-filter assembly procedures, we do not depend on the time consuming bending and pulling of coupling structures, which is not very reproducible. Using sophisticated simulation tools and production techniques, we are able to accurately calculate and manufacture the filter resonators and coupling structures. This enables us to accurately implement and verify theoretical results.

II. YIG-Filter fundamentals

The principle of YIG-bandpass-filters is based on the ferrimagnetic resonance of YIG spheres. Their frequency of resonance is proportional to a magnetic field provided by an electromagnet. The microwaves are coupled into and out of the YIG spheres by perpendicular, preferably loop-shaped conductors as shown in Fig. 1. Several of such filter stages can be combined to setup a multi-stage filter.

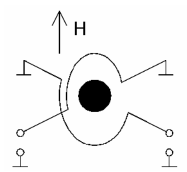

Fig. 1 YIG-sphere with orthogonal wire coupling in a magnetic field H

This principle is well known since the late 1950s [1],[2]. YIG filters have evolved since then, reaching increased tuning ranges, and 3-50 GHz filters have become commercially available [3],[4]. A typical YIG filter has a body with several connected chambers, each containing a perpendicular pair of wire loops and a YIG sphere which is mounted on a turnable ceramic rod. Multi-octave high-frequency filters require particularly small structures with sphere diameters as small as 250 µm. In order to fulfill the high demands of modern top-class spectrum analyzers, YIG filters should offer low ripple (1,5-2 dB), low insertion loss (<5 dB) and good return loss within a guaranteed bandwidth. Further, high selectivity, low thermal drift and fast tunability is required.

To ensure these properties over the full tuning range, a very accurate choice of coupling parameters is required. This depends on the choice of sphere parameters (surface quality, magnetization, diameter), coupling loop shape and size, transmission lines between the filter stages and the environment surrounding the filter stages. Furthermore, the crystallographic orientation of the spheres is crucial to the filter shape and the thermal behavior.

III. Modeling the YIG-filter

Based on the equivalent circuit of a single YIG resonator stage [5], a model for a four-stage YIG-filter will be developed.

A. Equivalent Circuit for a single YIG-stage

The Z-matrix of a single YIG-stage as shown in Fig. 1 can be described using the gyrator circuit of Fig. 2.

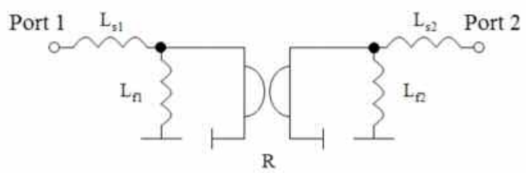

Fig. 2 Equivalent circuit of a single YIG-stage (YS) using a gyrator

The elements L_{f1}, L_{f2} and the gyrator ratio R model the YIG resonator and can be calculated in terms of the radius and magnetization of the sphere, the magnetic field and the radii and angles of the wire loops. They are related to the resonance frequency by

$$f_0 = \frac{R}{2\pi\sqrt{L_{f1}L_{f2}}} = \gamma H$$

with the gyromagnetic ratio γ and the magnetic field H. L_{s1} and L_{s2} account for the self inductances of the loops [5]. For our investigations, their values were obtained by 3D EM simulation of the loops and housing with the YIG-sphere represented as a dielectric (i.e. non-resonant) sphere.

B. Equivalent circuit for a four stage filter

We will use a series connection of four circuits from Fig. 2, mutually connected and connected to the ports by short transmission lines to model the complete four stage YIG-filter.

As a first step, the resulting five transmission lines will be replaced by five inductances L_{I}, L_{II} ... L_{V} (Fig. 3).

The circuit is supposed to be symmetric with respect to the middle inductance L_{III}.

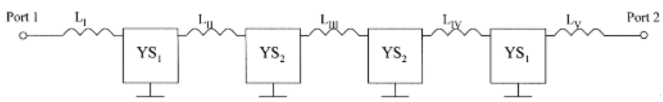

Fig. 3 Complete YIG-filter with YIG-stages YS_1-YS_4 coupled by L's

IV. LC-Equivalent Circuit

The circuit of Fig. 3 can be simplified and linked to classical filter synthesis theory by removing the gyrators with the following steps. If a parallel-L in a series circuit changes place with a gyrator, it is transformed to a series-C, and a series-L becomes a parallel-C, respectively. See Fig. 4 for the transformations.

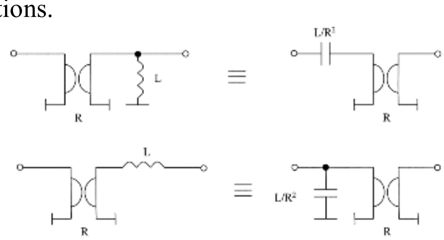

Fig. 4 Exchange of a gyrator with L or C

These transformations allow all gyrators to be removed from the circuit, as:

- Two adjacent gyrators with the same value of R cancel each other and may be omitted
- A single gyrator at a port of the circuit may be omitted by scaling the port impedance by R^2.

The resulting LC-filter circuit that is equivalent to the YIG-filter in Fig. 3, is shown in Fig. 5.

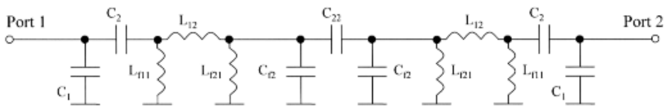

Fig. 5 LC-circuit resulting when gyrators are removed

V. YIG-Filter Synthesis

The resulting circuit of Fig. 5 is a well known top-L and top-C coupled bandpass filter. The synthesis of this circuit is straightforward using the methods given in [6], when a filter type, center frequency and 3 dB bandwidth are chosen. Once the elements for the LC filter are known, by stepping back through the transformations of Fig. 4, all parameters of the YIG-filter can be calculated. This synthesis procedure will provide a YIG-filter that matches the ideal filter prototype at the particular design frequency for which it is calculated.

In the resulting YIG-filter the resonance frequency of the first and last YIG-stage is slightly different (by 0.1 ... 0.3 %) compared to that of the two middle stages, requiring a difference in the magnetic field. This frequency shift obtained from filter theory here explains the need of a small angle between the pole pieces of the electromagnet, in a real YIG-filter adjusted by shims.

Further simulative analysis of the designed YIG-filter over the frequency tuning range by varying the value for the magnetic field shows that the filter curve deteriorates when the filter is detuned from its design frequency. This behavior is already expected from real YIG-filters. Our simulations showed that a design frequency at roughly $^2/_3$ of the tuning range – about 28 GHz for a 40 GHz filter – will give best results. However such a filter will not yet meet the specifications over the whole tuning range as can be seen in Fig. 6.

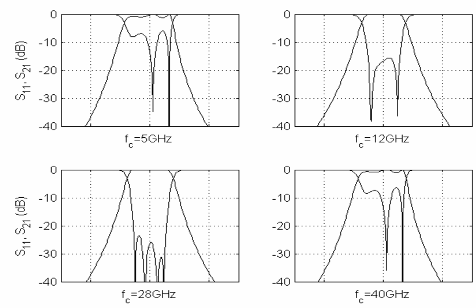

Fig. 6 Simulated filter characteristic of a YIG-filter. The design frequency was 28 GHz.

To further improve the filter design it is obviously necessary to accept a less than perfect performance at the design frequency to improve the filter at the lower and upper boundary of the tuning range. To prove this, a computer program was written to optimize the filter design. The program analyzes the YIG-filter equivalent circuit at several center frequencies over the whole tuning range and numerically optimizes the performance by changing loop radii and the shim parameter using a multidimensional simplex method [7]. The goal of the optimizer is a minimum of return loss (S_{11}) within the required 3 dB bandwidth. The analytically designed filter is used as a starting point for the optimizer. The resulting optimized filter performance can be seen in Fig. 7. For the filter analysis in the optimization program, the short transmission lines connecting the YIG stages are modeled as transmission lines, not as L's as in the analytical solution. As is visible in Fig. 7, the filter modeled with transmission lines shows a 3 dB bandwidth that increases with increasing center frequency. This behavior is typical for YIG-filters and often included in the specification. The calculated increase in bandwidth from our simulations is in very good agreement to the measured bandwidths of the filters manufactured.

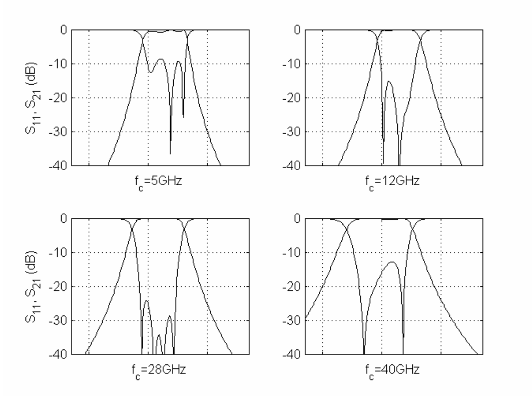

Fig. 7 Filter characteristic after numerical optimization over the tuning range.

VI. YIG-FILTER ASSEMBLY AND ALIGNMENT

As all physical parameters for the desired filter characteristics are determined as described in the previous sections, our goal was to manufacture and assemble the filter exactly according to these results. This is achieved as follows.

In order to have full control over the YIG crystal and sphere properties, we grow our own doped crystals and fabricate highly polished YIG spheres of the required diameters of 0.25 mm and 0.30 mm. They are mounted to ceramic rods in [110] orientation. Magnetization, diameter and resonance linewidth of each sphere were measured.

The filter body (Fig. 8) holding the YIG-assemblies and coupling loops is fabricated from German silver using wire eroding technique. German silver allows precise mechanical fabrication and suppresses eddy-currents sufficiently well due to its low electrical conductivity. The body is then electroplated with a thin layer of gold for best high frequency properties. All functional elements of the body are fabricated with tolerances of no more than 20 µm. In the center, there are four cylindrical holes to hold the spheres and coupling loops. Up to 30 GHz, cylinder diameters of 1.1 mm are used. Smaller cylinders of 0.8 mm are required for filters up to 50 GHz in order to avoid self-resonance of the coupling loops.

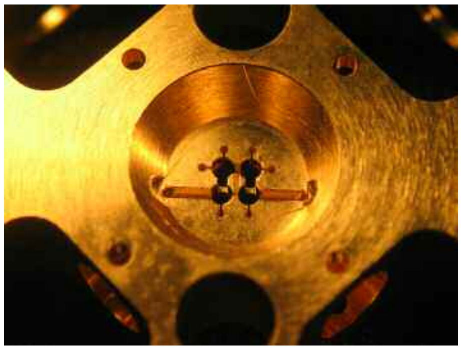

Fig. 8 Filter body holding the YIG spheres and coupling loops

A photolithographic process is used to etch the loops with an accuracy of less than 5 µm from a 50 µm thick sheet of copper-beryllium. Loop diameters and lengths are determined by our filter synthesis procedure. Rectangular plates at both ends of the pair are used for mounting the loop pairs in the body. They fit into the slots next to each of the cylinders in the body shown in Fig. 8. Each sheet of loops is measured optically in an automatic procedure to ensure each loop has the required diameter within specified tolerances of 5 µm.

The next step of filter assembly is the placement of the YIG spheres in the center of the loops. This step is of crucial importance, since any off-center placement of the sphere has a negative influence on the desired filter characteristics. We have investigated the influence of sphere displacement. Fig. 9 shows the filter curve of a filter where one of the spheres is 35 µm off-center.

This results in a VSWR of 3.0 at the center of the filter curve. With the sphere properly placed in the center, the VSWR is better than 2.0.

In order to achieve such accurate placement of the spheres, a sophisticated procedure of sphere positioning is required.

The rods holding the spheres are put into bushings and their ends are attached to very precisely adjustable xyz-mounts.

The filter body is mounted on a heatable socket that is placed in the center of a fixture comprising four of the described xyz-mounts as shown in Fig. 10. This fixture is placed under a measurement microscope, allowing to determine the relative position of focused contours to an accuracy of 2 µm in lateral and 4 µm in the vertical direction. With the help of this instrument and the fixture, the spheres can be positioned precisely in the center of the coupling loops. Being in this correct position, the bushings then are glued to the filter body. The heat from the socket is used to solidify the glue. This procedure allows a positioning of the spheres at the loop centers with an accuracy of 10 µm.

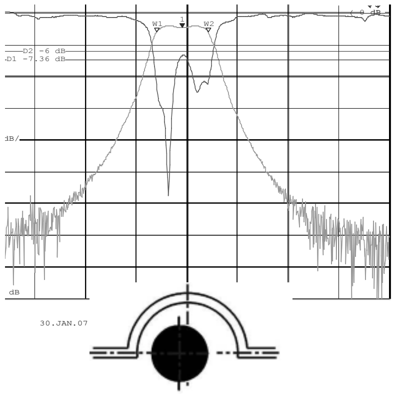

Fig. 9 Filter curve with one sphere placed 35 µm off-center

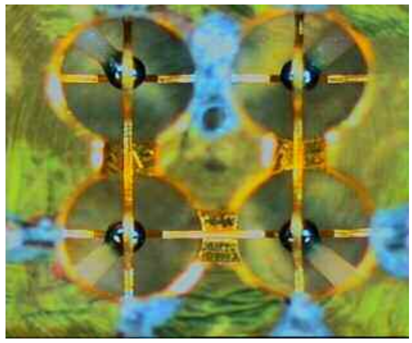

Fig. 11 View of the inner part of the filter body. The four pairs of etched CuBe loops are precisely positioned and soldered in the body using mounting slots. The four YIG spheres are placed in the center of the coupling loops.

After this assembly, the only degree of freedom left is to turn the rods in their bushings to set the spheres to the desired crystallographic axis.

Fig. 10 Fixture to position the YIG spheres exactly in the center of the coupling loops inside the filter body

The assembled filter body shown in Fig. 11 is now closed with a CuBe plate and mounted in the magnet housing. This fully assembled YIG filter is aligned using a vector network analyzer. The rotatable spheres are the only elements that need alignment. Using the integrated heaters they are set to their temperature stable axis and aligned. The only additional adjustable element is a shim used to introduce a small angle between the two parts of the magnet housing. This is necessary to ensure that all of the four resonators have the required tuning characteristics, as predicted by theory. Because of the precise assembling procedure, no reopening of the filter is required during the alignment that can be done easily and within a very short time. In a last step, all relevant filter parameters are measured to ensure that they are within the specifications.

VII. Conclusions

We have developed methods of simulating and manufacturing YIG filters so accurately that the time consuming procedure of after-assembly alignment could be minimized. A two-step filter synthesis procedure consisting of a mathematical synthesis of a YIG-filter that provides a starting point for a subsequent numerical optimization is described. The method was used to calculate all geometrical parameters of a YIG-filter design. The whole procedure of assembling and aligning the filter can be done in reproducible steps, allowing us to implement and verify theoretical results and reproducibly build reliable filters. This is particularly true for high frequency filters such as 40 or 50 GHz filters involving very small elements.

Acknowledgment

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