Tuning superconducting microwave filters by laser trimming

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***Abstract* — At present, superconducting filters are usually tuned using screws, but there are many reasons to seek an alternative. Laser trimming is an attractive choice. A laser trimming system is described that can tune a high temperature superconductor microstrip filter while it is cooled and connected to a network analyser. Software has been written to control the system, fit measured data and modify a filter design to account for unintended couplings. The residual material left after trimming $YBa_2Cu_3O_{7-\delta}$ has been shown to have negligible microwave loss. The system has been used to tune a simple three-resonator filter.**

I. Introduction

The use of high temperature superconductors (HTS) allows high performance microwave filters to be made in microstrip. Like other high performance filter technologies (e.g. waveguide), they cannot be designed or manufactured to sufficient accuracy to avoid the need for tuning. Even if they could be modelled perfectly, material properties such as the substrate thickness are not known with enough accuracy to ensure that the circuit is 'right first time'.

The usual solution to this problem is to incorporate mechanical tuning screws in the device packaging, allowing resonator frequencies and/or couplings to be adjusted after fabrication. This is a time-consuming process that requires an experienced microwave engineer, and its automation or simplification has been a subject of increasing interest to filter manufacturers in recent years.

For all-pole filters, a technique has been proposed [1] in which the filter response is compared to the design response in the time domain. This makes the tuning process more logical and less reliant on intuition. A more general approach is the development of fitting techniques capable of extracting circuit parameters from the measured filter response [2]. These can be used as a guide to the tuning of all types of filter and may ultimately be incorporated in an automatic process.

HTS filter manufacture would benefit from going beyond improving the efficiency of the tuning process to eliminating the use of tuning screws altogether. The screws increase the microstrip package size considerably, reduce its mechanical integrity and limit the packing density of resonators in the filter layout. Removing them would allow the development of highly miniaturised devices with low heat capacity and surface area, yielding reduced cooldown time and cooling power requirements. Such issues will increase in importance as the number of HTS filters included in a system increases.

In this paper we describe a tuning technique using laser ablation to modify a microstrip filter layout. Though mechanical milling has been used in an automatic tuning process for conventional microstrip filters [3], we are not aware of any other tuning technique for HTS filters that involves physical modification of the microstrip circuit.

The laser trimming is performed with the filter cooled to its operating temperature and connected to a Vector Network Analyser (VNA) so that the device response can be measured at each stage of the tuning process and used to provide guidance for further trim operations. By fitting the measured data to extract filter parameters, we can make a comparison with the original design and make modifications to account for the effects of unintended couplings.

The results presented here are for a simple three-resonator filter and represent a proof of principle for the technique. The ultimate goal is to incorporate laser trimming in an automated tuning system for high order HTS filters.

II. The Laser Trimming System

The hardware (Fig. 1) comprises a miniature dye laser mounted on the illuminator unit of an optical microscope. A nitrogen UV laser with 4 ns pulse length excites the dye cell via a fibre optic cable. This produces a secondary beam of 440 nm wavelength that is focussed to a spot approximately 2 μm in diameter. The pulse energy incident on the device that is required for ablation is difficult to measure accurately but is estimated to be 2 μJ. The microscope assembly is moved over a quartz window in the cryostat chamber by a 3D micro-positioning stage, with a full movement range of ±20 mm from the window centre. A video camera mounted on the illuminator unit provides TV images of the device.

In the control software, an electronic copy of the device layout is transformed to the absolute co-ordinate system of the translation stage. The transformation incorporates microscope focussing, allowing the user to navigate the device by selecting points on the map. Once a rectangular

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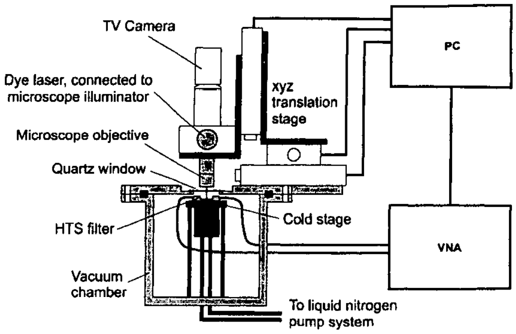

Fig. 1. Schematic of laser trimming system.

trim area has been defined, the laser beam is automatically rastered over the region with a step size approximately equal to the laser spot radius.

The filter response can be observed on the VNA while trimming is taking place and full 2-port data can be stored by the control software after each trim operation.

III. Laser trimming $YBa_2Cu_3O_{7-\delta}$

The laser power, scan speed and pulse rate can be varied to operate in different regimes, ranging from surface melting of the HTS film to full ablation. Fig. 2 shows scanning electron microscope (SEM) images of the damage to a $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film caused by individual laser pulses at these two extremes.

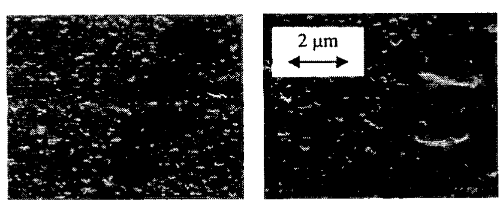

Fig. 2. SEM micrographs of YBCO ablated by individual laser pulses. (Left) surface melting, low power (Right) full ablation, high power. For trimming devices, repetition rate and scan speed are adjusted so that adjacent spots overlap.

Investigation of the electrical properties of laser-trimmed YBCO has shown that it is necessary to operate in the full ablation regime when tuning filters. In this experiment, a 2 μm wide track across the middle of a microstrip resonator was trimmed repeatedly with increasing laser power and measurements of the fundamental and second harmonic modes were used to extract information on the degradation of the trimmed region. The resonator was a simple 2 GHz half-wavelength 1 mm wide microstrip section patterned on a double-sided YBCO/MgO wafer, with weak coupling to ensure a measured Q close to the unloaded value.

Data from selected stages of the experiment have been plotted in Fig. 3. Before trimming, the measured Q of the fundamental resonance was 37,000, and there was no observable reduction in this value well into the regime where surface melting occurred. In the transition from surface melting to full ablation the trimmed material became lossy, degrading and then completely destroying the fundamental resonance. At this point the second harmonic was unaffected, as this mode has zero current at the resonator centre. Full ablation is required to separate the resonator into a strongly coupled pair of resonators with two modes near the frequency of the original second harmonic. Though the Q of the modes was degraded with the narrow 2 μm coupling gap, the values improved as the gap was widened by further laser trimming.

By modelling the coupling between the resonator halves as a lumped capacitor with a shunt resistor, the sheet resistance of the 2 μm wide region between them has been estimated as 65 MΩ per square. The residual material left after trimming gives rise to negligible loss in all but the narrowest of gaps.

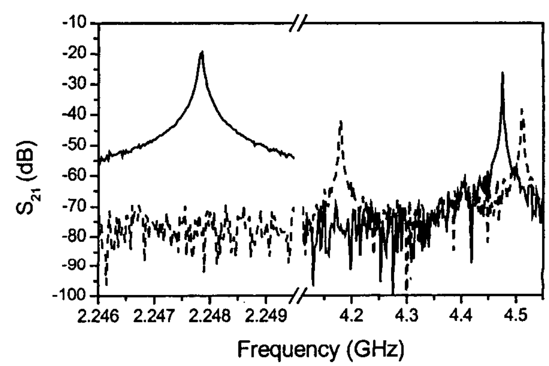

Fig. 3. Effect on the fundamental and second harmonic modes of a microstrip resonator as laser trimming is used to split it in two. Before trimming (solid line) the measured Q-values for the two modes are 37,000 and 15,000. After full electrical separation (dashed line) the two modes are destroyed and replaced by the fundamental modes of a strongly coupled resonator pair, with Q-values of 5,000 and 10,000. These values improve to 13,000 for each mode as the coupling gap is widened from 2 to 22 μm.

IV. Filter tuning process

Given the irreversible nature of a laser trim operation, it is essential that decisions on how to tune a filter be based on accurate knowledge of its current properties. Extraction of filter parameters from measured data is thus a key component of the laser tuning system, and at the heart of this process lies the ability to model a filter accurately. In contrast to conventional technologies, the challenge of HTS filters is that in a typical high Q microstrip layout it is necessary to include both intended and unintended couplings between resonators. The most natural approach is to represent all possible couplings in a matrix [4]. Lumped element models alone do not give exact descriptions of distributed resonator circuits; the filter model must incorporate sufficient generality to give an accurate description of its physical behaviour [5].

Even if a lumped element model were exact, a single dataset (S_{11}, S_{21} and S_{22}) would not provide enough information to deduce all the physical parameters of the filter: the solution is not unique. We solve this problem by acquiring a tuning series of data and fitting them all simultaneously, allowing only those parameters that have been tuned to vary between successive datasets in the fit.

The tuning process can be summarised as:

(1) Fit a model to a data series acquired with different tunings, in order to extract filter parameters for the device.
(2) Assess which filter parameters can realistically be modified.
(3) Predict the changes in these filter parameters that will produce a tuned response by performing an optimisation process.
(4) Convert the desired filter parameter tunings to physical trims of the layout, using derivative information from the fit obtained in step 1.
(5) Trim the filter to produce this result.

The initial fit of step 1 is usually based on a series of small tunings. The derivative information extracted from it may therefore have a limited range of validity, restricting the accuracy of the predictions of required trim area in step 4. It is therefore prudent to perform the trims in a series of increments, refining the derivative information by fitting new data as it is acquired. It should be noted that in a manufacturing process it would be possible to accumulate substantial knowledge of the tuning behaviour for a particular filter layout. This extra information could be used to enhance the accuracy of the trim area predictions and reduce the number of intermediate steps.

In the next section we demonstrate this process by tuning a 3-section filter. The data presented are a subset of those actually measured, and the 'predictions' have been produced by reanalysis of the data after completing the tuning process. The actual predictions used during tuning were based on a simpler model that produced poorer fits, but gave essentially the same guidance.

V. Tuning a 3-Section Filter

A 3-section pseudo-elliptic filter was designed using simple microstrip $\lambda/2$ resonators at approximately 8 GHz. The frequency was chosen to enable device fabrication from a 1 inch double-sided YBCO/MgO wafer. The device layout (Fig. 4) was produced using Touchstone software to optimise a microstrip circuit model. Though the accuracy of this process is limited, the device response was close enough that laser trimming could be used to optimise the filter.

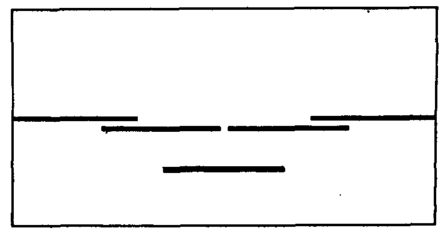

Fig. 4. 3-section filter layout.

In this layout, the only readily adjustable parameters are the input couplings, the resonator frequencies and the cross-coupling between the input and output resonators. The couplings can only be reduced, while it is easier to increase the resonator frequencies than to reduce them. In this example, the only resonators that have been tuned are the input and output resonators: the middle one has been considered as fixed.

Fig. 5 shows a fit to three datasets that quantify the effect of tuning the input and output resonators. Associated with these tunings is a decrease in the cross-coupling; this has been allowed to vary in fitting the data.

Having established the coupling matrix that describes the filter, the next step is to produce an optimised target matrix that will yield the desired filter response. The optimisation target was minimum in-band insertion loss and only those parameters that we wished to tune were allowed to vary. The filter response predicted by the optimiser is shown in Fig. 6 as the dashed line.

The input and output resonators were then shortened so as to approach the frequencies in the target matrix, leading ultimately to the measured response plotted in Fig. 6. The predictive accuracy of the optimisation process improves if it is performed at a starting point that is closer to a tuned filter.

The final filter has a bandwidth of 54 MHz at 7.958 GHz, with a maximum in-band insertion loss of approximately 0.9 dB.

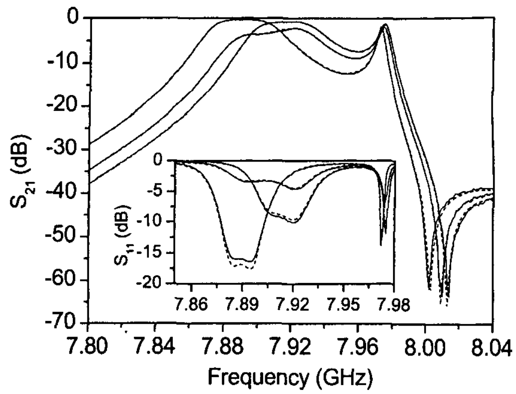

Fig. 5. Fits to S_{21} and (inset) S_{11} at three different tunings of the 3-section filter (solid curves experiment, fits shown as dashed). T = 69 K.

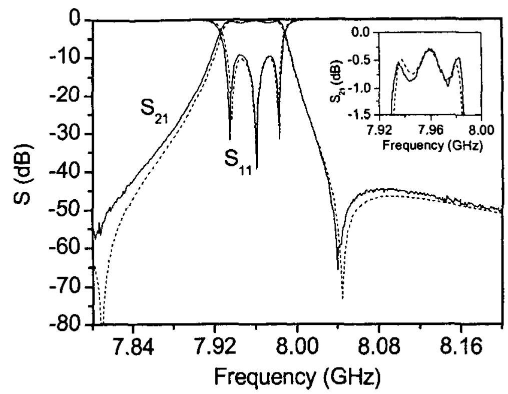

Fig. 6. Comparison of predicted filter response (dashed curve, deduced from fits of Fig. 5) and data measured after tuning (solid curve). The inset shows an expanded view of the passband. T = 69 K.

VI. CONCLUSION

We have demonstrated laser tuning of a simple microstrip filter. The equipment is able to trim devices at ~70 K, enabling continuous monitoring of the microwave characteristics during trimming. Fits to tuning series of measured data allow filter parameters to be extracted and provide guidance during trimming operations. The quality of the fits obtained is believed to be good enough that accurate tuning of complex filters will be possible.

It is envisaged that laser trimming could provide an efficient design, fabrication and manufacture process, without the need for bulky tuning screws. It will make prototyping filters more efficient by reducing the need for mask iterations, making it practical to fabricate one-off filters for specialist applications. With further development of the software, automated tuning in production would reduce costs and improve filter performance, as the design could be optimised to account for the specific characteristics of each device.

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