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A miniaturized HTS microwave receiver front-end subsystem for radar and communication applications

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ABSTRACT

This paper presents a miniaturized high performance high temperature superconducting (HTS) microwave receiver front-end subsystem, which uses a mini stirling cryocooler to cool a high selective HTS filter and a low noise amplifier (LNA). The HTS filter was miniaturized by using specially designed compact resonators and fabricating with double-sided YBCO films on LAO substrate which has a relatively high permittivity. The LNA was specially designed to work at cryogenic temperature with noise figure of 0.27 dB at 71 K. The mini cryocooler, which is widely used in infrared detectors, has a smaller size (60 mm × 80 mm × 100 mm) and a lighter weight (340 g) than the stirling cryocoolers commonly used in other HTS filter subsystem. The whole front-end subsystem, including a HTS filter, a LNA, a cryocooler and the vacuum chamber, has a size of only φ120 mm × 175 mm and a weight of only 3.3 kg. The microwave devices inside the subsystem are working at 71.8 K with a consumed cooling power of 0.325 W. The center frequency of this subsystem is 925.2 MHz and the bandwidth is 2.7 MHz (which is a fractional bandwidth of 0.2%), with the gain of 19.75 dB at center frequency and the return loss better than −18.11 dB in the pass band. The stop band rejection is more than 60 dB and the skirt slope is exceeding 120 dB MHz^{-1}. The noise figure of this subsystem is less than 0.8 dB. This front-end subsystem can be used in radars and communication systems conveniently due to it's compact size and light weight.

1. Introduction

After the discovery of high temperature superconductor (HTS) in 1986, great effort has been placed to develop electronic devices using HTS [1]. In all the applications, the most widely studied field is HTS filter subsystem, which generally consists of HTS filters, LNAs, a vacuum chamber and a cryocooler [2]. HTS filters have a low insertion loss and a high selectivity, and LNAs have lower noise figures at cryogenic temperature than at room temperature [3]. When combined into a cryogenic system, they have a much higher sensitivity and selectivity than conventional room temperature filters system, and can be used in mobile communication, radar and other systems as receiver front-end subsystems [4–6].

Although the HTS filter subsystems have excellent microwave properties, their applications are restrained by their relatively big size and high weigh caused by the use of cryocoolers. In this project, we use a mini cryocooler to cool a miniaturized HTS filter and a cryogenic LNA, so the size and weight of the subsystem was reduced remarkably while it still has very high selectivity and low noise figure. Because the cryocooler has relatively small cooling power companied with the reduction in size and weight, the microwave devices it cooled must be miniaturized and special methods must be taken in the subsystem integration to reduce the heat leak. The design of HTS filter and LNA are presented in parts 2 and 3, respectively. In part 4 the integration of the subsystem is described in details. And the experimental results are described in part 5.

2. Miniaturized design of the HTS filter

The filter was designed to have a center frequency of 925.5 MHz, which was specified by a wind-profiler radar. A very high selectivity of the filter was required to prevent interference to or from closely neighboring mobile phone signals. For our design, the filter has a fractional bandwidth of 2.9‰, stop band rejection of more than 60 dB and the skirt slope exceeding 120 dB MHz^{-1}. As well known, small fractional bandwidth means weak couplings between the resonators of the filter, which correspond to large distance between the resonators. High stop band rejection and skirt slope means large numbers of resonators

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needed in filter design. All those factors will increase the filter size.

A 10-pole quasi-elliptic function response with a pair of transmission zeros was selected for the filter instead of the traditional Chebyshev function response, because it need much more resonators for Chebyshev function response than quasi-elliptic function response to realize the same selectivity. Theoretical calculation shows that a 12-pole Chebyshev filter would be needed to realize the same skirt slope as our 10-pole quasi-elliptic filter. As shown in the inset of Fig. 1, an ultra-compact dual-spiral structure microstrip resonator was employed in our design. This type of resonator has demonstrated very weak far-field radiation so that they can be arranged very close to each other but still have a weak coupling [7]. Fig. 1 shows the simulated coupling coefficient k between two adjacent resonators using the full-wave EM simulation software Sonnet as a function of spacing s. It can be seen that k decreases rapidly with s. When s changes from 0.25 to 2.07 mm (about a resonator's width), the coupling coefficient k becomes more than three orders of magnitude less than its original value, making this resonator very suitable for ultra-narrow bandpass filter design. The filter was further miniaturized by being fabricated with double-sided YBCO films on LAO substrate. The permittivity of LAO is about 23.6 which is the highest in all the commonly used HTS substrates. The size of our resonator with a resonant frequency of 925.5 MHz is 10.41 mm $\times$ 0.98 mm. If a MgO substrate with a permittivity of 9.6 is used, the resonator size will be 20.9 mm $\times$ 2 mm.

The final filter layout is shown in Fig. 2. The whole filter including the brass house has a dimension of only 35 mm $\times$ 27 mm $\times$ 20 mm. The filter was measured at 71.8 K and it showed excellent performance with insertion loss at 925 MHz being 0.26 dB, return loss over the whole pass band better than 18 dB, band-edge skirt slope exceeding 120 dB MHz^{-1} and rejection at the stop band better than 60 dB, as shown in Fig. 3.

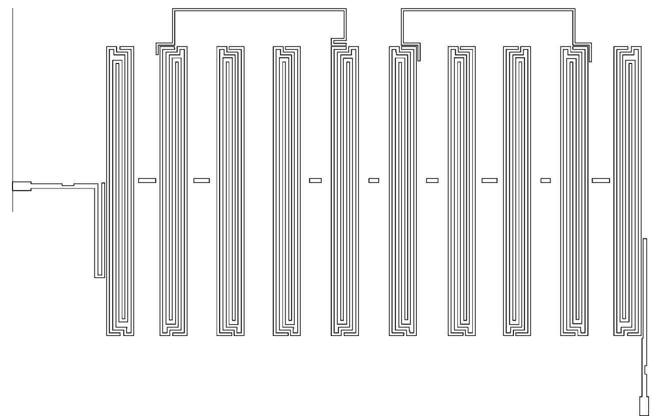

Fig. 2. Layout of the 10-pole quasi-elliptic filter.

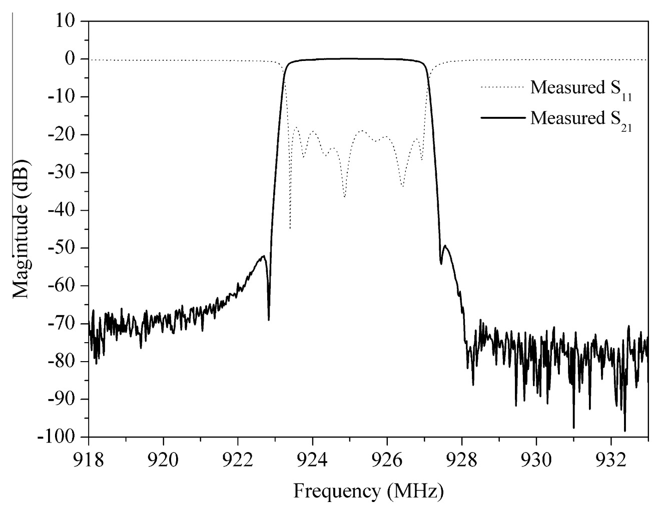

Fig. 3. Measured results of the 10-pole HTS filter.

3. Cryogenic design of the LNA

The noise figure of LNA decreases drastically when working at cryogenic temperature. However the physical and electronic characteristics of the transistor at low temperature deviate from that at room temperature. Usually, the S-parameter at the operation temperature is needed before design. However, cryogenic S-parameter test equipment is very expensive and it also takes a lot of time to measure the low temperature S-parameter. To reduce the cost and time, a room temperature S-parameter was used and two necessary correction methods were made in our design. One is to estimate the trend of the S-parameter from room temperature to cryogenic temperature with the help of EM software Ansoft Serenade. The other is to reduce the drain-to-source current properly which can make low temperature S-parameter close to that at room temperature.

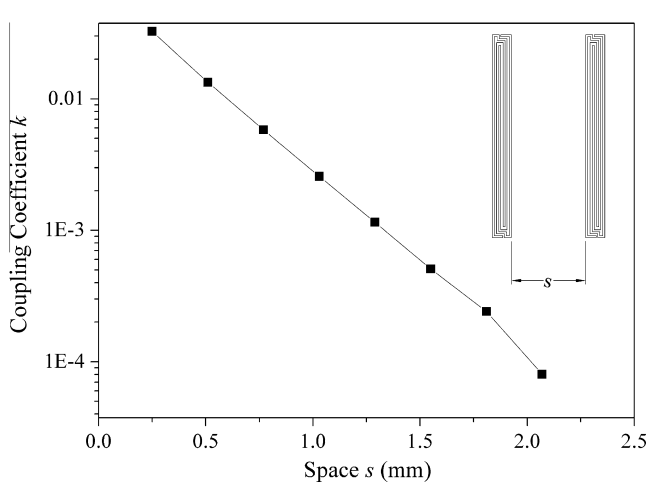

Fig. 1. Simulated coupling coefficient k as a function of space s and the dual-spiral structure microstrip resonator.

Special attention should also be paid to the self-oscillation of the transistor when working at low temperature. The materials and passive components with high temperature stability are chose in the circuit. A commercial high electron mobility transistor (HEMT) Fujitsu FHR10X was selected in our design. In order to improve the stability and input match, inductive feedback was employed using bond wires connecting the transistor source to the ground. In order to achieve the lowest possible noise temperature, the most critical part is the amplifier input circuitry. The 50 Ω input line (from SMA connector) has to be transformed into a complex impedance varying with frequency that should be as close as possible to the optimum noise match of the transistors. The output-circuits were optimized for maximum gain, gain flatness, and output match.

The noise figures of this cryogenic LNA measured at different temperatures are shown in Fig. 4, where decreasing of the noise figure from about 0.92 dB at 287.9 K down to about 0.27 dB at 71 K can be clearly seen.