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A Superconducting 180° IF Hybrid for Balanced SIS Mixers

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Abstract—**A compact 180° hybrid has been developed for use in balanced SIS mixers. The lumped-element circuit uses superconducting Nb conductors on a 1.4 mm x 0.5 mm quartz substrate and operates over 4-12 GHz.**

Index Terms—**Superconducting microwave devices, microwave integrated circuits, hybrid junctions, lumped-element microwave circuits, superconductor-insulator-superconductor mixers.**

I. INTRODUCTION

Balanced mixers have several advantages for use in low-noise millimeter-wave receivers: (i) Sideband noise from the local oscillator is substantially reduced. (ii) The LO power required by a balanced mixer is typically 17 dB less than for a similar single-ended mixer. (iv) The dynamic range of a balanced mixer is twice that of a similar single-ended mixer. (iii) No external LO diplexer is required in the signal path. Balanced mixers are therefore appropriate when the lowest system noise is desired, particularly when LO noise is significant. For receivers in which many mixers are driven by a common LO, such as a focal plane array, the low LO power requirement of balanced mixers greatly simplifies LO generation and distribution.

The simplest balanced mixer uses a pair of single-ended mixers with the IF outputs connected in parallel. However, this requires the two mixers to be biased oppositely and presents undesirable IF impedance levels to the in-phase and out-of-phase IF components from the individual mixers. The use of an IF hybrid, as shown in Fig. 1, provides a desirable IF impedance environment for the SIS mixer elements while allowing them to be biased by a common supply. This paper describes a superconducting 180° hybrid for 4-12 GHz, small enough to be mounted inside a balanced mixer block. The hybrid can be used in cryogenic balanced mixers for any RF band.

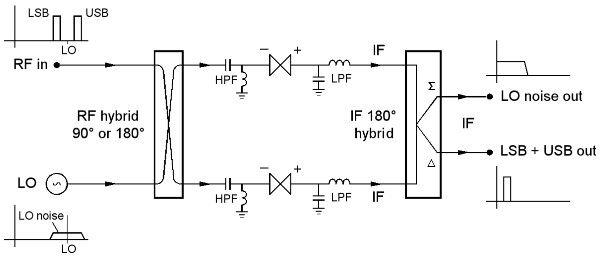
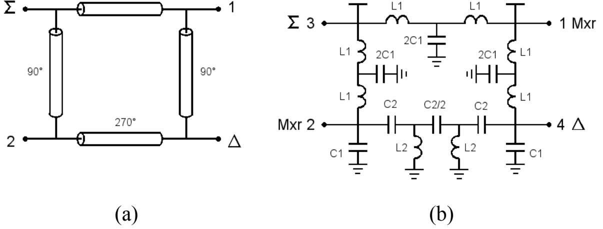


Fig. 1. Balanced SIS mixer with the same bias polarity on the two component mixers.

The requirements for the IF hybrid in a balanced SIS mixer are: (i) both even and odd mode IF signals from the SIS mixers should see a 50-ohm load, (ii) the hybrid should have a DC path which allows both mixers to be biased through the hybrid by a single bias source, (iii) the load (IF amplifier) impedance is 50 ohms; and (iv) the hybrid should be small enough to mount inside the balanced mixer block.

Hybrids can be made in sevaral ways. Below about 1 GHz, small transformers with three windings can be used but at higher frequencies, transmission line circuits based on the rat-race design (Fig. 2(a)) are used. Because of the quarter and three-quarter wavelength lines, these are too large for convenient incorporation into a balanced mixer. The size can be reduced greatly by using a lumped-element design.

The lumped-element design of Parisi [1] is based on the rat-race hybrid and uses lumped-element transmission lines. The number of elements is greatly reduced by replacing the 270° line with a 90° *negative transmission line*. This is shown in Fig. 2(b), in which three arms of the circuit are 90° LC transmission lines and the fourth (bottom) arm is a 90° LC negative transmission line. Another lumped-element design, the lattice hybrid [2], uses lattice sections to emulate positive and negative transmission line sections, and can have very wide bandwidth, but it requires balanced sources and loads to



(a) (b)

Fig. 2. (a) Rat-race hybrid. (b) The Parisi hybrid, in which the 270° transmission line is replaced by a 90° negative transmission line .

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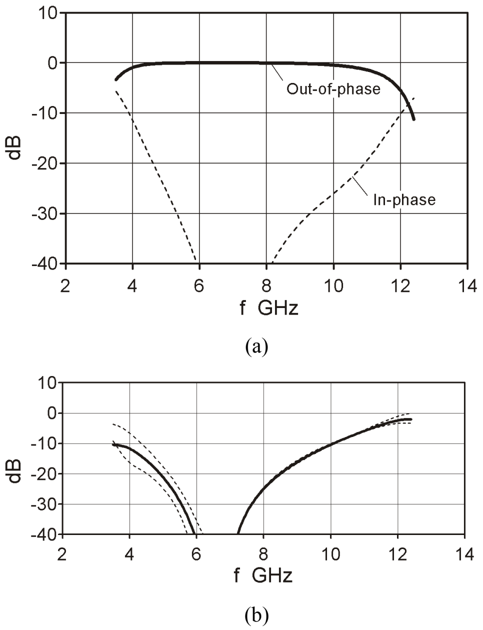


Fig. 3. Characteristics of the Parisi hybrid using the original element values. (a) Coupling to port 4 when ports 1 and 2 are excited in-phase (dashed line) and out-of-phase (solid line). (b) Reflection coefficient at port 2 when ports 1 and 2 are excited in-phase, out-of-phase (dashed lines), and with port 1 not excited (solid line).

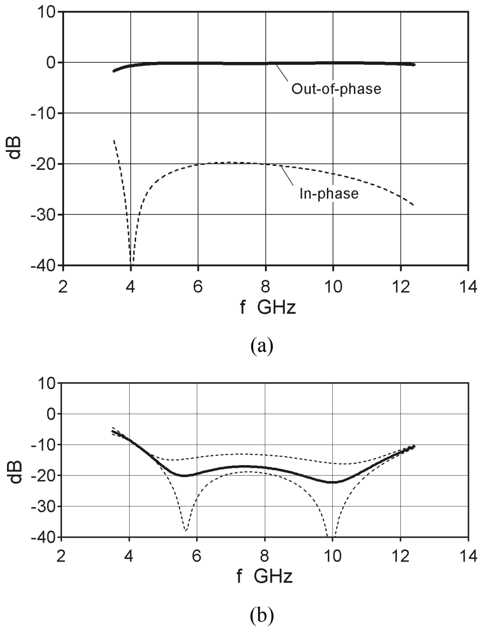


Fig. 4. Characteristics of the modified Parisi hybrid. (a) Coupling to port 4 when ports 1 and 2 are excited in-phase (solid line) and out-of-phase (dashed line). (b) Reflection coefficient at port 2 when ports 1 and 2 are excited in-phase and out-of-phase (dashed lines) and when port 1 is not excited (solid line). (Source impedances 50 ohms.)

operate correctly. In the present work, a modified version of the Parisi design is used.

II. DESIGN

Using Parisi's circuit element values, scaled to a center frequency of 8 GHz, the circuit has the response shown in Fig. 3. Figure 3(a) shows the coupling to port 4 when the mixer ports 1 and 2 are excited by equal amplitude signals out of phase (corresponding to the desired IF signal from the balanced mixer) and in phase (corresponding to the down-converted LO sideband noise). Figure 3(b) shows the return loss at port 2 as seen by a test signal when port 1 is terminated in 50 ohms or excited in or out of phase with the test signal, as occurs in an operating balanced mixer.

It was found that the circuit element values could be adjusted to give a better response over the desired 4-12 GHz band. Figure 4 shows the result of optimization with the criteria $S_{42} + S_{41} = 0$, $S_{32} - S_{31} = 0$, $S_{11} < -20$ dB, and $S_{22} < -20$ dB.

The IF output impedance of an operating SIS mixer can be much higher than 50 ohms. The characteristics of the optimized hybrid connected to 400-ohm sources at ports 1 and 2 are shown in Fig. 5. The coupling curves are normalized to the power that would be delivered to a 50-ohm load by the 400-ohm sources. For port 1 and 2 source impedances greater than 400 ohms, the characteristics change only slightly. (Note that it is not generally desirable to impedance match the IF amplifier to the (high) output impedance of an SIS mixer. While matching may improve the transducer gain of the mixer and reduce the receiver noise temperature somewhat, it is likely to degrade the RF input match of the mixer, even to the point of causing reflection gain, and reduces the dynamic range of the mixer.)

The hybrid was fabricated on a fused quartz substrate using niobium conductors. Inductors were planar spirals, and parallel plate capacitors had a SiO_x dielectric. The layout of the chip is shown in Fig. 6. Parasitic reactances are not negligible and are included in the equivalent circuit of Fig. 7. The parallel capacitance of the inductors and the

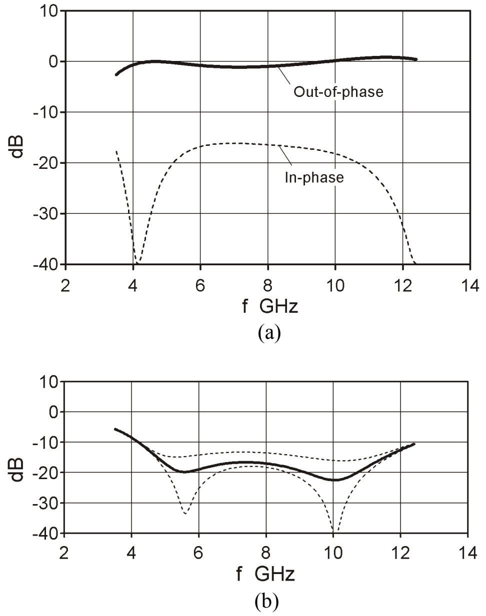


Fig. 5. Characteristics of the modified Parisi hybrid with 400-Ω sources at ports 1 and 2. (a) Coupling to port 4 when ports 1 and 2 are excited in-phase (solid line) and out-of-phase (dashed line). (b) Reflection coefficient at port 2 when ports 1 and 2 are excited in-phase and out-of-phase (dashed lines), and when port 1 is not excited (solid line).

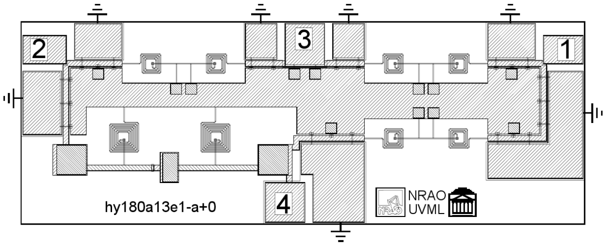


Fig. 6. Layout of the hybrid on a quartz chip. Dimensions: 1.42 mm x 0.51 mm.

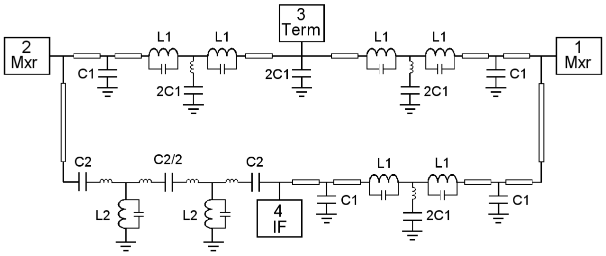


Fig. 7. Equivalent circuit of the Parisi hybrid on a chip as shown in Fig. 6, including parasitic elements.

series inductance of the capacitor leads are included, and long conductors are represented as transmission lines.

Inductors for the initial chip layout were designed to the values of the re-optimized Parisi circuit using Sonnet *em* [3], and capacitor dimensions were calculated using the simple parallel plate formula. The layout was then simulated using Sonnet, and the circuit simulator MMICAD [4] was used to find the values of the parasitic inductances and transmission line parameters by fitting the circuit response to the Sonnet simulation. Once the parasitic element values had been found in this way, a final optimization of the main elements, L_1, L_2, C_1, C_2, was done using MMICAD. Figure 8 shows the final Sonnet and MMICAD results.

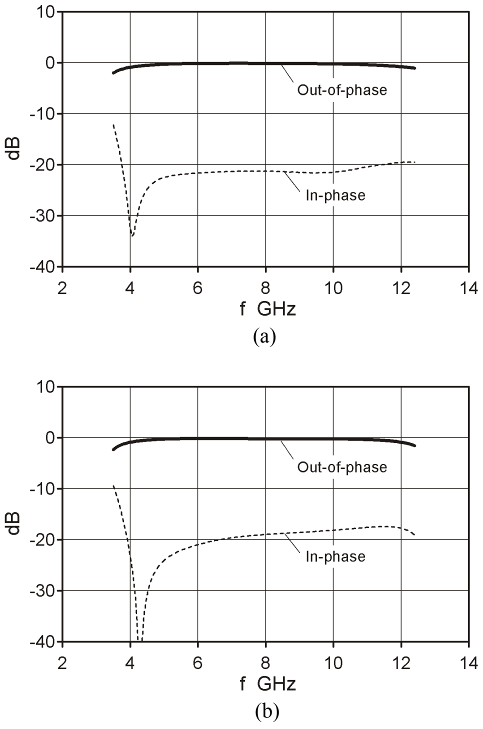


Fig. 8. (a) Sonnet simulation of the layout in Fig. 6. (b) MMICAD simulation of the circuit in Fig. 7. Showing the coupling to port 4 when ports 1 and 2 are excited in-phase and out-of-phase. All ports terminated in 50 ohms.

III. FABRICATION

The hybrids are fabricated on a 250-µm fused quartz substrate in three layers: a lower conductor, an SiO_X insulating layer, and an upper Nb "wiring" layer. The lower conductor is sputter-deposited as a Nb/Ti/Nb sandwich (75/15/75 nm) with a protective overlayer of CrAu (30 nm). It is then patterned through a photoresist mask using a wet etch for the CrAu and reactive ion etching the Nb/Ti/Nb layer. Photoresist is then applied to mask the CrAu areas over which a dielectric layer is not desired, and 285 nm SiO_X is sputter deposited and patterned by liftoff. The upper Nb layer is sputter deposited over the entire wafer, followed by gold. The gold forms contacts to diagnostic capacitors elsewhere on the wafer but is removed from the area of the hybrid. The upper Nb is patterned by photolithography with RIE. In this RIE, the CrAu contact pads of the hybrid are revealed. During this etch, the thin Ti in the lower conductor prevents complete removal on the Nb around the perimeter of CrAu features neither edge-sealed by SiO_X nor fully covered by the upper Nb.

IV. MEASUREMENTS

The hybrids were tested in the four-port 50-ohm fixture shown in Fig 9. Measurements were made with two ports

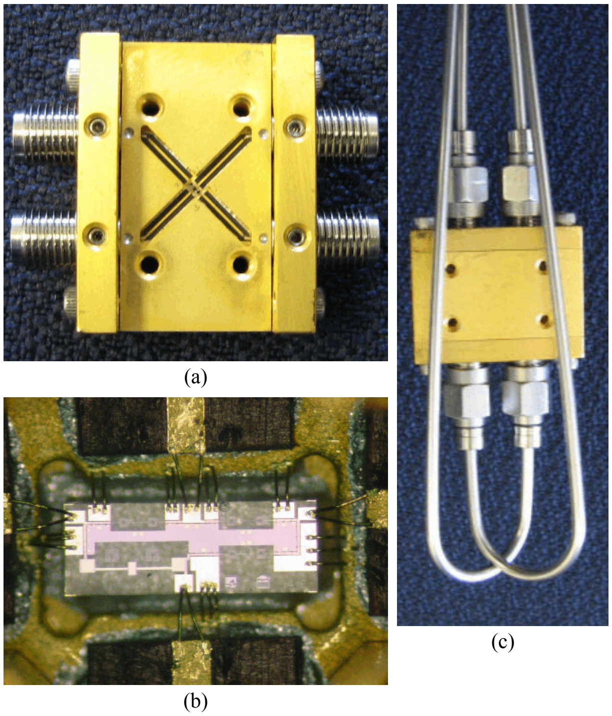


Fig. 9. (a) The four-port test fixture. (b) The hybrid chip in the test fixture showing wire bonds to the four microstrip lines and to ground. (c) The test fixture connected to four stainless-steel cables for immersion into a liquid helium storage dewar.

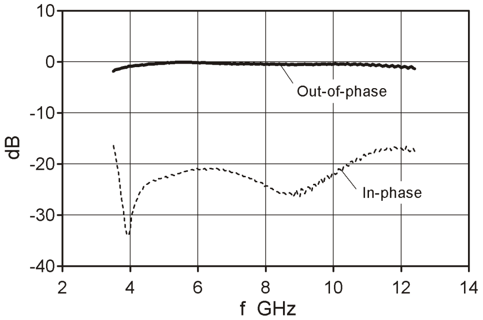
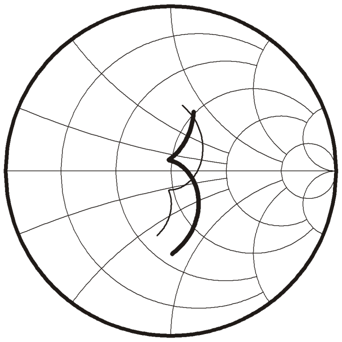


Fig. 10. Measured characteristics of the hybrid. Coupling to port 4 when ports 1 and 2 are excited in-phase and out-of-phase.

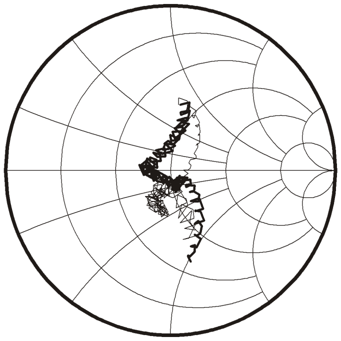
of the hybrid connected to the VNA and the other two ports terminated in 50-ohm loads. This two-port measurement was repeated six times until all combinations of ports had been measured — hence, all S-parameters of the hybrid.

As VNA calibration at the ends of cables in a liquid helium dewar is impractical, calibration was done at the room-temperature interface. The cables and test fixture were then measured, with the hybrid chip disconnected, while dipped in liquid helium, and an equivalent circuit derived for each cable connected to the test fixture. The S-parameters of the hybrid were then able to be de-embedded from measurements at the room temperature ends of the cables.

Figure 10 shows the coupling to port 4 when ports 1 and 2 are excited in-phase and out-of-phase, computed from the de-embedded S-parameter measurememts (all ports terminated in 50 ohms).



(a)



(b)

Fig. 11. Reflection coefficient at ports 1 (wide line) and 2 (narrow line) over 4-12 GHz. (a) Sonnet simulation. (b) Measured.

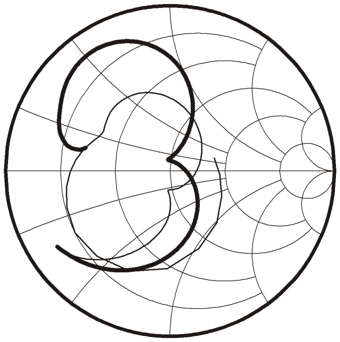


Fig. 12. Reflection coefficient at ports 1 (wide line) and 2 (narrow line) over 2-14 GHz. Sonnet simulation.

Figure 11 shows the reflection coefficient seen by each mixer connected to the hybrid.

V. DISCUSSION

The superconducting hybrid is seen to operate as designed over the 4-12 GHz band. It meets the criteria given in the introduction for use in a balanced SIS mixer. The even-mode rejection at port 4 is greater than 16 dB, which is sufficient to suppress LO sideband noise effectively in a balanced mixer. The two unit mixers can be biased in parallel from port 4 (the IF amplifier port) as long as a blocking capacitor is added in series with the 50-ohm termination on port 3. Operation of the hybrid with mixers whose IF output impedance is much larger than 50 ohms is similar to that with 50-ohm mixers. The load impedance seen by mixers connected to the hybrid is near 50 ohms within the 4-12 GHz band and is well behaved out of band as indicated in Fig. 12 (which is from the Sonnet simulation).

It is of interest to note that if the superconducting niobium is replaced with 300 nm gold conductors, for operation at room temperature, the loss of the hybrid increases by > 5 dB.

ACKNOWLEDGMENT

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