Band-Splitting Diplexing-Hybrid for Dual-Band Simultaneous-Observing Sideband-Separating Heterodyne Mixers

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ABSTRACT

Simultaneous multi-band observations with heterodyne receivers offer significant advantages for astronomical applications requiring broad spectral coverage or frequency phase-transfer calibration, such as very-long-baseline-interferometry (VLBI) observations conducted by the Event Horizon Telescope (EHT). However, simultaneous multi-band operation is typically achieved using free-space optical diplexers, which introduce additional loss and noise when implemented in ground-based cryogenic receiver systems.

In this work, we present a novel band-splitting diplexing-hybrid architecture that enables simultaneous dual-band observations while preserving the sideband-separating (2SB) functionality of modern superconductor–insulator–superconductor (SIS) receivers. The proposed concept extends the simultaneous-observing multi-band receiver (SOMBR) approach by integrating frequency-selective diplexing functionality directly into the RF quadrature-hybrid network required by a conventional 2SB receiver. As a demonstration, a dual-band architecture covering ALMA Bands 5 and 6 (163–275 GHz) is investigated.

A broadband superconducting quadrature-hybrid chip based on a three-section branch-line coupler was designed and analysed using full-wave electromagnetic simulations. The hybrid was combined with straight rectangular waveguide sections as high-pass filters to realise an integrated diplexing-hybrid network capable of routing Band 5 and Band 6 signals to independent receiver chains while simultaneously providing the quadrature power division required for sideband separation. Simulation results demonstrate the feasibility of the proposed architecture, achieving broadband power division and frequency-selective routing across the combined Band 5+6 frequency range. Although further optimisation is required to improve amplitude balance and return-loss performance, particularly at the lower edge of Band 5, the results establish the viability of integrating simultaneous dual-band and 2SB functionality within a compact superconducting circuit. The proposed architecture provides a potential pathway towards low-loss, cryogenically compatible multi-band SIS receivers for future astronomical instrumentation.

Keywords: Quadrature hybrid, Diplexer, Superconducting chip, Broadband, Simultaneous observing, Band-combining, Multiple band operation, Sideband separating, SIS mixers

1. INTRODUCTION

Modern superconductor–insulator–superconductor (SIS) mixers have enabled ultra-sensitive astronomical observations in the millimetre (mm) and sub-mm wavelength regimes. These heterodyne detectors routinely achieve sensitivities approaching the quantum noise limit. Current development efforts are focused on expanding both the radio-frequency (RF) and intermediate-frequency (IF) bandwidths of SIS receivers to meet the requirements of the Atacama Large Millimetre/sub-millimetre Array (ALMA) Wideband Sensitivity Upgrade (WSU) programme.[1] In parallel, there is growing interest in increasing the pixel count of heterodyne receiver arrays to facilitate efficient large-area sky mapping for future facilities.

SIS receivers also form the core detection technology of the Event Horizon Telescope (EHT),[2] a global very-long-baseline interferometry (VLBI) array operating at mm and sub-mm wavelengths that synthesises an Earth-sized telescope to image the immediate environment of supermassive black holes. For such observations,

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simultaneous multi-band operation is highly desirable, as it enables phase-transfer calibration,[3] whereby phase information measured at a lower observing frequency is used to calibrate observations at higher frequencies, thereby improving coherence and sensitivity.

Simultaneous observations across multiple RF bands have previously been demonstrated, particularly in space-borne instruments, through the use of free-space diplexing optics such as dielectric- and metamaterial-based dichroic filters. However, this approach is less attractive for ground-based observatories because the optical diplexers are typically mounted on relatively warm receiver stages, introducing additional insertion loss and associated thermal noise that degrade the overall receiver sensitivity. Consequently, simultaneous multi-band spectroscopic observations remain relatively uncommon in ground-based heterodyne astronomical receivers.

In this contribution, we present a novel band-splitting diplexing-hybrid architecture that replaces conventional lossy free-space diplexers with a cryogenic diplexer that can potentially be integrated on-chip with the SIS mixers or implemented as a separate superconducting circuit. A related concept has previously been demonstrated by Masui et al.,[4,5] who realised single-sideband (SSB) operation across four fixed-frequency bands, thereby demonstrating the feasibility of superconducting on-chip frequency-selective architectures. Building upon this concept, the proposed design enables simultaneous dual-band observations while retaining the sideband-separating functionality required for broadband heterodyne spectroscopy.

2. DESIGN CONCEPT

In this work, we extend the simultaneous-observing multi-band receiver (SOMBR) concept demonstrated by Masui et al.[4,5] to enable tunable sideband-separating (2SB) operation across multiple RF bands. The concept is illustrated using a dual-band SOMBR design covering the frequency range of ALMA Bands 5 and 6.

2.1 Conventional Sideband Separating Mixer

Before introducing the proposed SOMBR architecture, it is useful to briefly review the operating principle of a conventional sideband-separating (2SB) SIS mixer. This architecture has been widely adopted in mm- and sub-mm wave astronomical receivers, including those deployed on ALMA, owing to its ability to separate the upper and lower sidebands and thereby improve observing efficiency compared with double-sideband (DSB) or single-sideband (SSB) operation.

In a double-sideband (DSB) receiver, both the upper-sideband (USB) and lower-sideband (LSB) signals are down-converted onto the same intermediate-frequency (IF) band. Specifically, signals at frequencies $\omega_{USB} = \omega_{RF} - \omega_{LO}$ and $\omega_{LSB} = \omega_{LO} - \omega_{RF}$ produce identical IF frequencies and are therefore superimposed in the detected spectrum. This overlap can lead to spectral ambiguity in astronomical observations. An SSB receiver avoids this issue by rejecting one of the sidebands prior to detection. In contrast, a 2SB receiver, illustrated in Fig. 1, separates the USB and LSB signals into two independent IF outputs. This approach recovers both sidebands simultaneously, effectively doubling the instantaneous RF frequency coverage relative to an SSB receiver with the same IF bandwidth, and has consequently become the preferred architecture for many modern SIS receiver systems.

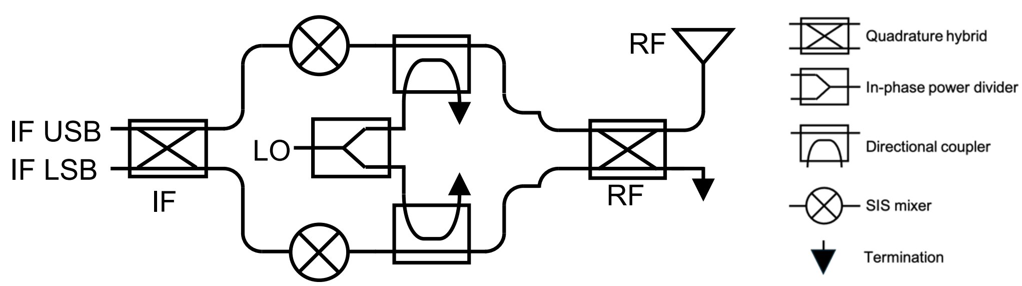


Figure 1. Circuit diagram depicting the architecture of a 2SB heterodyne receiver.

The enhanced functionality of a 2SB receiver is achieved at the expense of increased circuit complexity. Relative to a DSB or SSB receiver, a 2SB receiver requires an RF quadrature hybrid to divide the incoming

RF signal into two equal-amplitude components with a relative phase difference of 90°. These signals are then applied to a pair of DSB mixers, while the local oscillator (LO) signal is injected in phase. An equivalent implementation can be realised by applying the RF signal in phase and introducing a 90° phase shift in the LO path instead. Following frequency conversion, the IF outputs from the two mixers are recombined using an IF quadrature hybrid, which separates the USB and LSB components into two independent physical IF channels for subsequent signal processing.

2.2 Concept of a Simultaneous-Observing Dual-Band Mixer

Unlike fixed-frequency multi-band receiver concepts, the proposed architecture preserves the local-oscillator (LO) tuning capability of each constituent 2SB receiver. Consequently, simultaneous observations may be performed at arbitrary frequencies within the respective Band 5 and Band 6 RF ranges, while maintaining the flexibility of a conventional tuneable heterodyne system. The objective of the proposed architecture is to enable simultaneous observations in two independently tunable RF bands during a single observing campaign while relying primarily on cryogenically compatible components. To achieve this, we build upon the well-established 2SB receiver architecture and introduce only minimal modifications to the existing design. Fig. 2 illustrates how a pair of 2SB mixers can be combined to realise simultaneous dual-band observing capability through the incorporation of only two frequency-selective elements. As an illustrative example, we consider a receiver covering the combined frequency range of ALMA Bands 5 and 6. In this implementation, the frequency-selective elements are simple high-pass filters (HPFs), realised using rectangular waveguides with dimensions chosen such that the cut-off frequency lies at the boundary between Bands 5 and 6.

The astronomical RF signal collected by the broadband Band 5+6 antenna first enters an RF quadrature hybrid, where it is equally divided into two paths. Each path then encounters an HPF. Signals within Band 6 propagate through the HPFs and are routed to the receiver chain shown on the left-hand side of Fig. 2, thereby forming a conventional Band 6 2SB receiver. Conversely, signals below the HPF cut-off frequency are reflected by the filters and directed towards a second RF quadrature hybrid located on the right-hand side of Fig. 2. These reflected signals form the separated Band 5 2SB receiver chain.

Inspection of Fig. 2 reveals that the components highlighted in blue, together with one of the quadrature hybrids highlighted in purple, constitute a conventional Band 6 2SB receiver. Likewise, the components highlighted in red, together with the second quadrature hybrid, form an equivalent Band 5 2SB receiver. Relative to the conventional architecture shown in Fig. 1, the only additional elements required are the pair of HPFs that perform the RF band separation. This demonstrates that simultaneous dual-band operation can be realised by integrating a frequency-selective diplexing function into the RF distribution network already required by the 2SB architecture.

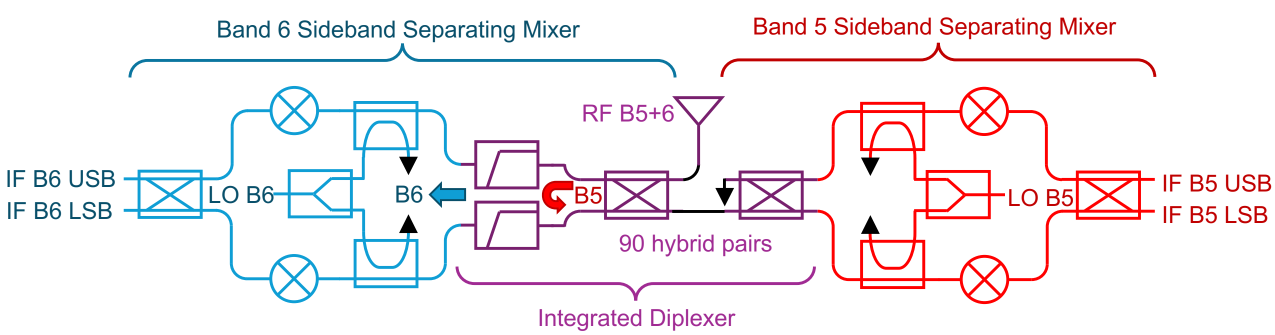


Figure 2. Circuit diagram depicting the concept of a Bands 5+6 SOMBR.

The principal distinction between the proposed SOMBR architecture and two independently implemented 2SB receivers is therefore the integrated diplexing section, shown in purple in Fig. 2. This section separates the incoming broadband RF signal into two frequency bands and simultaneously performs the RF power division required by the corresponding Band 5 and Band 6 receiver chains. Since the design and operation of 2SB SIS mixers are already well established, the remainder of this manuscript focuses on the design, optimisation, and electromagnetic characterisation of this integrated diplexing-hybrid network.

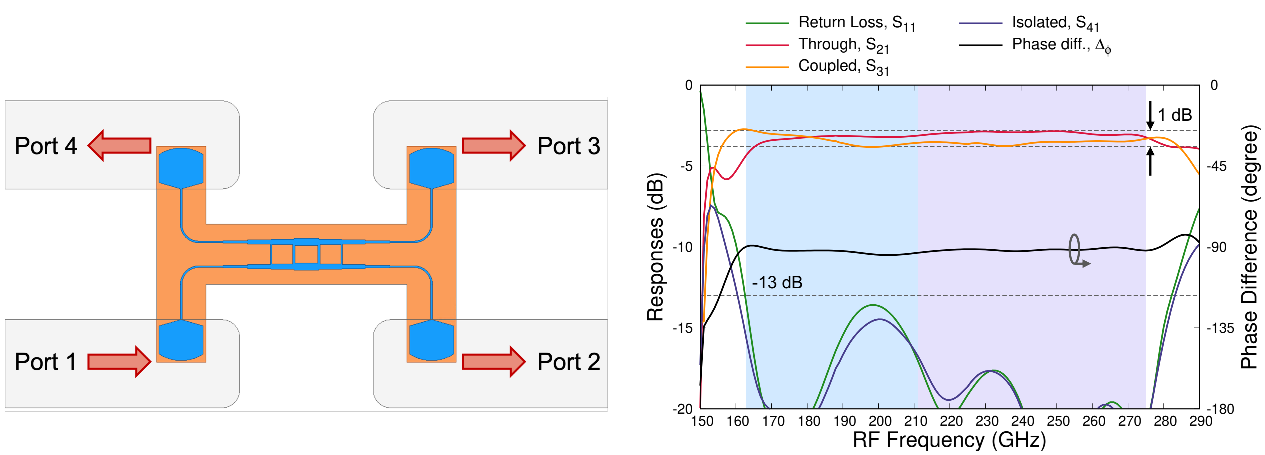
3. SUPERCONDUCTING QUADRATURE HYBRID

Since the RF quadrature hybrid is a key component of both conventional 2SB receivers and the proposed SOMBR architecture, we first introduce the design of a cryogenic superconducting quadrature-hybrid chip. The proposed device provides functionality equivalent to that of commercially available broadband microwave quadrature hybrids while remaining compatible with integration in SIS receiver front ends.

At the RF frequencies considered in this work (ALMA Bands 5 and 6; 163–275 GHz), implementation using conventional microwave cabling is impractical. Instead, the superconducting hybrid circuit is embedded within a waveguide environment and coupled to the incoming RF signal through a waveguide-to-planar-circuit transition. In the present design, this transition is realised using a radial microstrip probe.[6]

The quadrature-hybrid design presented here serves as the fundamental building block of the band-splitting diplexing-hybrid network described in the subsequent sections. Consequently, establishing a broadband, low-loss, and well-balanced quadrature response is essential for achieving both high sideband-separation performance and efficient dual-band signal routing.

3.1 Band 5+6 Quadrature Hybrid



(a) (b)

Figure 3. (a) Image showing the layout of the radial probe antenna coupled B5+6 hybrid. The dimensions shown are not to scale for clarity purposes. (a) Layout of the proposed waveguide-coupled B5+6 superconducting quadrature-hybrid chip with radial probe antennas as waveguide-to-microstrip transitions. Dimensions are not shown to scale for clarity. (b) Simulated scattering parameters and phase balance of the quadrature hybrid obtained using Ansys HFSS.

Fig. 3(a) shows the layout of the proposed broadband RF quadrature-hybrid chip corresponding to the component highlighted in purple on the right-hand side of Fig. 2. Although this hybrid is only required to operate over the Band 5 frequency range in the present architecture, the corresponding hybrid located on the left-hand side of Fig. 2 must support the full combined Band 5+6 frequency range. To simplify the design and fabrication process, the same broadband hybrid design is therefore adopted for both locations.

To achieve the required bandwidth, a multi-section branch-line coupler architecture comprising three cascaded branch-line sections was employed. This approach significantly broadens the operational bandwidth relative to a conventional single-section branch-line coupler, enabling coverage of the complete ALMA Band 5 and Band 6 frequency ranges. Fig. 3(b) presents the simulated performance of the broadband quadrature hybrid obtained using Ansys® High Frequency Structure Simulator (HFSS). The simulation assumes superconducting niobium microstrip transmission lines deposited on a 10 µm silicon membrane substrate,[7] separated from the ground plane by a thin silicon-oxide dielectric layer.

The simulated results demonstrate that the hybrid provides near-equal power division across the entire 163–275 GHz frequency range, with an amplitude imbalance within 1 dB difference between the two output ports. The phase difference between the output signals remains close to the ideal quadrature value of 90° throughout the operating band. In addition, the input return loss remains better than −13 dB across the full Band 5+6 frequency range, indicating good broadband impedance matching.

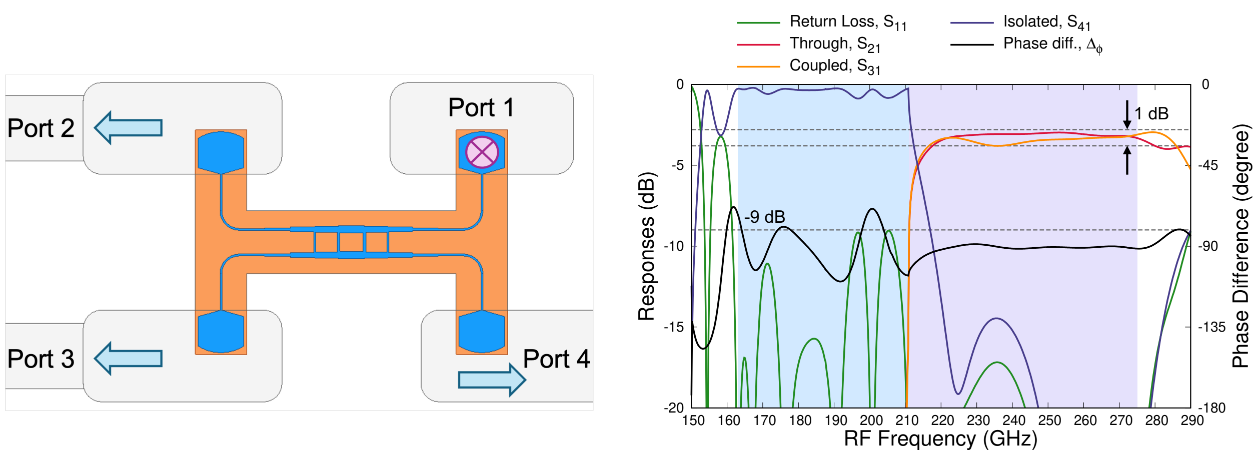
3.2 Band 5+6 Quadrature Hybrid with High-Pass Filter

The broadband B5+6 quadrature hybrid described in the previous subsection is used as the basis for the second hybrid stage (left-hand side of Fig. 2) within the integrated diplexing-hybrid network. To realise the required frequency-selective functionality, a pair of high-pass filters (HPFs) is incorporated at the output ports of the hybrid. For the present proof-of-concept design, the HPFs are implemented using straight waveguide sections with appropriately chosen cross-sectional dimensions. The resulting structure is illustrated in Fig. 4(a), while the simulated performance is presented in Fig. 4(b).

It should be noted that an equivalent implementation could be realised using low-pass filters (LPFs) instead of HPFs. In such a configuration, the relative locations of the Band 5 and Band 6 receiver chains shown in Fig. 2 would simply be interchanged, while the overall operating principle would remain unchanged.

The integrated component simultaneously performs quadrature power division and RF band separation. Signals within the higher-frequency Band 6 range are transmitted through the HPFs and emerge from Ports 2 and 3 with approximately equal amplitude and the required quadrature phase relationship. In contrast, lower-frequency Band 5 signals are reflected by the HPFs and routed towards Port 4, where they are subsequently processed by the second quadrature-hybrid stage of the SOMBR architecture shown earlier in Sec. 3.1.

The simulated performance shown in Fig. 4(b) confirms that the device fulfils these requirements. Across the Band 6 frequency range, the power split between Ports 2 and 3 remains balanced to within approximately 1 dB, while the relative phase difference remains close to the ideal value of 90°. At the same time, strong rejection of the higher-frequency signals is observed at Port 4, demonstrating effective frequency discrimination between the two observing bands. Although the overall functionality is successfully achieved, the simulated return-loss performance indicates that further optimisation is desirable, particularly within the Band 5 frequency range, where impedance matching remains less satisfactory than in Band 6.



(a) (b)

Figure 4. (a) Layout of the quadrature-hybrid chip incorporating integrated high-pass filtering functionality. Dimensions are not shown to scale for clarity. The RF signal is expected to enter the device through Port 1 with the wide-face of the probe antenna aligned perpendicular to the direction of the RF power flow. In this case, the rectangular waveguide for Port 1 is oriented orthogonally to the remaining three ports. The HPFs are shown as the narrow rectangular waveguide section of Port 2 and 3. (b) Simulated performance of the integrated quadrature-hybrid and high-pass-filter structure.

4. FULL DIPLEXER SIMULATION

Fig. 5 (a) shows the layout of the complete integrated diplexing-hybrid network, comprising two B5+6 quadrature hybrids and a pair of straight-waveguide HPFs. The corresponding electromagnetic simulation results obtained using Ansys HFSS are presented in Fig. 5 (b).

To aid interpretation, the broadband astronomical RF signal is assumed to enter the network through Port 1 (top-down into the page). The signal first encounters the quadrature hybrid on the left-hand side of the structure, where it is equally divided between two paths containing the HPFs. Signals within the Band 6 frequency range are transmitted through the HPFs and emerge from the two output ports with approximately equal amplitudes and the required quadrature phase relationship, thereby forming the RF input to the Band 6 2SB receiver. Conversely, Band 5 signals are reflected by the HPFs and propagate back through the same quadrature hybrid. These reflected signals recombine at Port 4 and are subsequently routed to the second quadrature hybrid on the right-hand side of the structure. The second hybrid then equally divides the Band 5 signal into the two RF paths required by the Band 5 2SB receiver.

The simulated performance of the complete diplexing-hybrid network is shown in Fig. 5 (b). Overall, the results confirm that the proposed architecture successfully achieves the intended functionality. Both the Band 5

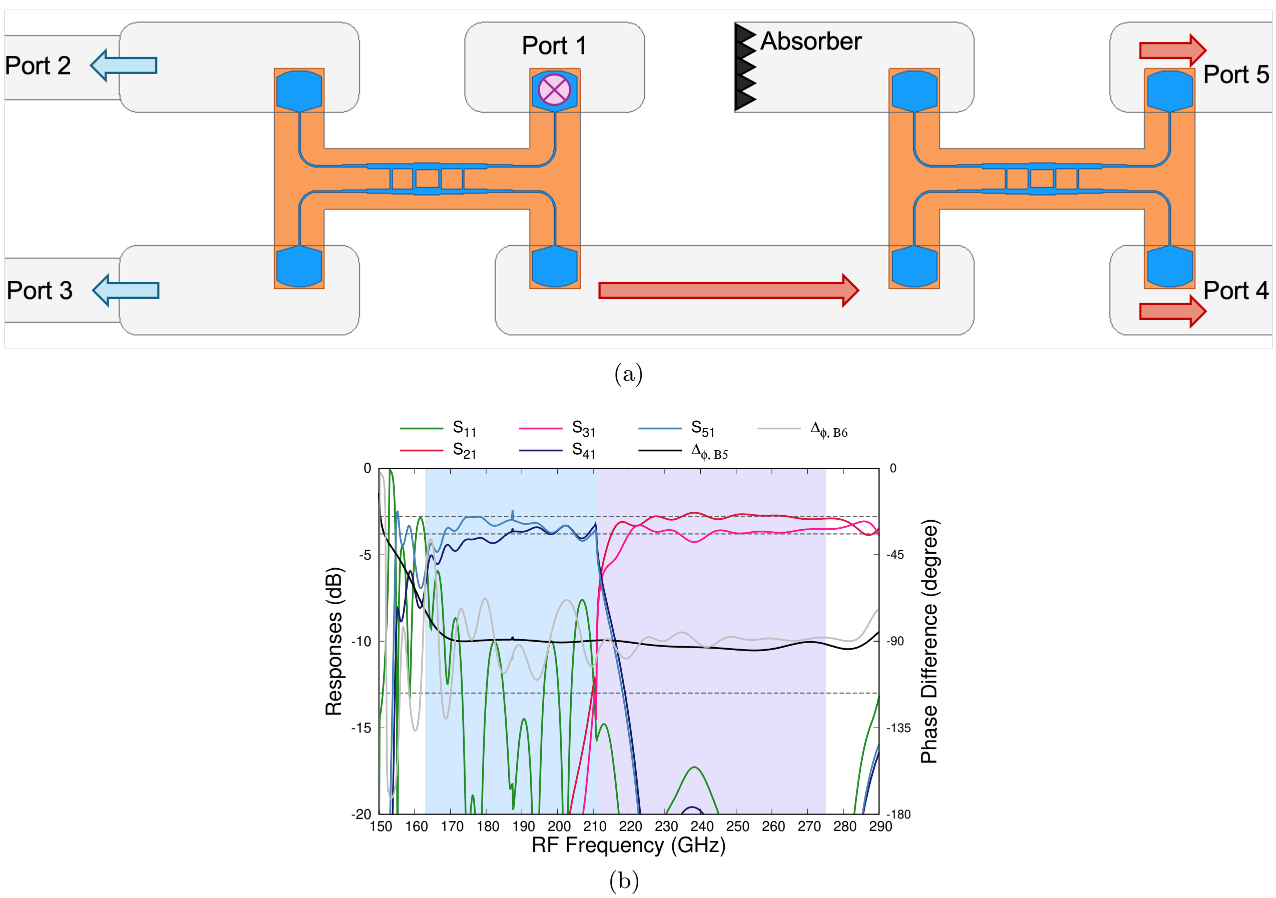


Figure 5. (a) Layout of the integrated diplexing-hybrid comprising a set of B5+6 quadrature hybrid and a pair of HPFs in the form of straight rectangular waveguides shown as the narrower section of waveguides to the left of the figure. The broadband B5+6 RF signal enters Port 1, with the diplexed Band 6 signal exits through Port 2 and 3 with equal amplitude and a 90° phase difference. Band 5 RF signal is reflected by the HPFs, recombined through the first quadrature hybrid on the left, then entering the quadrature hybrid on the right to produce equal amplitude Band 5 signal at Port 4 & 5 with 90° phase difference. (b) Simulated performance of the integrated diplexing-hybrid network comprising a set of quadrature-hybrids and a pair of high-pass-filters.

and Band 6 receiver branches exhibit approximately equal power division between the corresponding RF mixer inputs, demonstrating that the integrated structure simultaneously performs frequency-band separation and quadrature power splitting.

The simulation results also reveal several areas in which further optimisation is warranted. Although the output power division remains close to the ideal –3 dB level across most of the operating band, the amplitude imbalance is not consistently maintained within a 1 dB tolerance across the full Band 5+6 frequency range. The degradation is most pronounced at the lower edge of Band 5, where the return loss, amplitude balance, and phase balance all deteriorate relative to the remainder of the band. In contrast, the Band 6 receiver branch exhibits superior return-loss performance and generally more favourable amplitude balance, although its phase response shows somewhat greater variation across the band.

These trends are consistent with the behaviour already observed for the quadrature-hybrid and HPF sub-assembly in Fig. 4 (b), indicating that the performance limitations originate primarily from the integrated filtering stage rather than the overall system architecture. Nevertheless, the simulation demonstrates the feasibility of the proposed diplexing-hybrid concept and suggests that further optimisation of the filtering and matching structures should yield improved amplitude balance, phase balance, and impedance matching across both observing bands.

5. CONCLUSION

We have presented a novel band-splitting diplexing-hybrid architecture for simultaneous-observing dual-band sideband-separating SIS receivers. The proposed concept extends conventional 2SB receiver architectures by integrating frequency-selective diplexing functionality directly into the RF quadrature-hybrid network, thereby enabling simultaneous observations in two independently tuneable RF bands while preserving sideband-separation capability.

To demonstrate the concept, a dual-band receiver covering ALMA Bands 5 and 6 was investigated. A broadband superconducting quadrature-hybrid chip based on a multi-section branch-line coupler was designed and analysed using full-wave electromagnetic simulations. By integrating waveguide high-pass filters with the quadrature hybrid, a compact diplexing-hybrid network was realised that simultaneously performs RF band separation and quadrature power division. Electromagnetic simulations confirm the feasibility of the proposed architecture and demonstrate successful routing of Band 5 and Band 6 signals to independent 2SB receiver chains across the combined 163–275 GHz frequency range.

Although the present implementation exhibits degraded performance near the lower edge of Band 5, particularly in terms of return loss, amplitude balance, and phase balance, these limitations appear to originate primarily from the current filtering and matching structures rather than from the underlying architecture itself. Consequently, further optimisation of the diplexing-hybrid network is expected to yield substantial improvements in overall performance. Future work will focus on optimisation of the integrated structure, fabrication of the superconducting circuit, and experimental validation through integration with SIS mixer devices.

The proposed SOMBR concept is readily extendable beyond the dual-band Band 5+6 implementation presented here. In principle, additional receiver bands may be incorporated by cascading further 2SB receiver chains, provided sufficiently broadband input antennas and first-stage quadrature hybrids are available. Such an approach appears feasible in light of previous demonstrations of ultra-broadband quadrature-hybrid structures covering bandwidth ratios approaching 6:1.[8]

More generally, the same architectural concept could be extended towards continuous frequency coverage across the entire ALMA frequency range without the need for tuneable local oscillators. In such a system, the broadband RF spectrum would be divided amongst a large number of narrower-band 2SB receiver channels, each operating with a fixed local oscillator frequency. While such an approach would significantly increase the number of receiver chains and backend processing requirements, it would provide simultaneous access to an unprecedented RF bandwidth and may be attractive for future spectroscopic survey instruments.

Finally, it is worth noting that a similar simultaneous-observing architecture could be realised using a conventional three-port diplexer to separate the Band 5 and Band 6 signals prior to the 2SB receivers. However, in such a configuration, each receiver branch would still require its own RF quadrature hybrid to realise sideband separation. The proposed diplexing-hybrid architecture therefore offers a more integrated solution by combining the diplexing and quadrature power-division functions within the same network. Whether this approach remains advantageous for future ultra-broadband SOMBR implementations will depend on the relative complexity of realising extremely broadband diplexers compared with broadband quadrature hybrids, a topic that requires further investigation.

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