Short-slot Hybrid Coupler Using Linear Taper in W-band

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Abstract -We have designed and fabricated a broadband short-slot hybrid coupler using a two-stage linear taper in W-band. The coupler consists of two metal pieces split at the edge of the narrow wall of the waveguide, which makes it possible to use simple direct machining for fabrication. The electrical performance of the coupler was measured by a Vector Network Analyzer (VNA) at room temperature. The results showed excellent performance as designed: amplitude imbalance between the two output ports of \( \leq 1 \) dB, phase difference between the output ports with respect to \( 90^\circ < 3^\circ \), input return loss \( < -15 \) dB, and isolation \( < -15 \) dB across the measured frequency range of 85-110 GHz. The short-slot hybrid coupler was used in a balanced Superconductor-Insulator-Superconductor (SIS) mixer at 4 K. The noise performance was almost the same as that of the two single-ended mixers used in the balanced mixer. These results indicate that our short-slot hybrid coupler has great potential for practical applications, such as at millimeter- and submillimeter-waves.

Keywords Short-slot hybrid coupler · Waveguide coupler · Balanced mixer · Superconductor-Insulator-Superconductor mixer

1 Introduction

Millimeter- and sub-millimeter-wave technologies have recently become increasingly important in many practical and basic scientific applications such as remote sensing, radio astronomy, plasma diagnostics, imaging, and communication. In particular, high-resolution heterodyne spectroscopy using ultra-sensitive detectors such as Superconductor-Insulator-Superconductor (SIS) junctions in the millimeter- and sub-millimeter-wave regions is important for astronomical research, since signals provide spatial information. Heterodyne receivers in the latest radio astronomical telescopes such as the Atacama Large
Millimeter/sub-millimeter Array (ALMA) employ sideband-separating (2SB) mixers with about 25% fractional bandwidth to cover the existing atmospheric windows [1]. In these mixers, waveguide quadrature hybrid couplers are used. At terahertz frequencies, where no powerful source is available at the moment, balanced mixers with a quadrature coupler are considered to be useful because the required local oscillator (LO) power can be substantially reduced, as well as the LO sideband noise.

Waveguide branch line couplers are widely used as wideband 3-dB quadrature couplers because robust and reliable designs are well established [2]. However, the fabrication technological complexity increases with frequency and it is challenging to manufacture these components at millimeter and sub-millimeter wavelengths. Typically, 3-dB branch-line directional couplers need a branch line width of about ~0.09 λg [3]. This width becomes very narrow for high frequencies and it is usually too narrow to be manufactured by conventional milling machines.

Alternatively, a short-slot hybrid coupler has a simple geometrical structure. However, a capacitive tuning screw or dome is often inserted in the coupling region to widen the operational bandwidth [4], which complicates the structure. It has been theoretically shown that a short-slot hybrid coupler using a circular taper without the complex tuning device provides reasonable performance with a bandwidth of about 28%: amplitude imbalance of < 1 dB, input return loss of < -20 dB, and isolation of < -20 dB in X-band [5]. In this study, we have designed and demonstrated short-slot hybrid couplers using linear tapers, which are much simpler and easier to manufacture than circular tapers, to try to improve the performance for possible practical applications at millimeter- and sub-millimeter wavelengths. We present the design and the experimental performance of a W-band two-stage linear tapered coupler. Finally, this coupler has been used in a balanced SIS mixer that shows excellent performance at a working temperature of 4 K.

2 Short-slot Hybrid Coupler

2.1 Design

A short-slot hybrid coupler consists of a suitably placed gap in the common narrow wall of two parallel waveguides [6]. The coupling region of the coupler acts as an oversized waveguide, with dimensions such that the TE10 (even) and TE20 (odd) modes can exist and the TE30 mode is in cutoff and non-propagative. The bandwidth of a short-slot hybrid coupler is limited by the generation of TE30 mode. Thus, the width of the interaction region must generally be reduced to prevent the propagation of the undesired TE30 mode [7]. The interaction region and the two adjacent rectangular waveguides need to be conjugate matched for broad bandwidth coupling. H-plane tapers are employed to achieve the impedance match.

Firstly, we started the design of a linear tapered short-slot hybrid coupler using the circular tapered short-slot hybrid coupler [5]. The four main parameters that we sought to optimize were the input return loss, transmission, coupling and isolation. We employed the three-dimensional electromagnetic field analysis software HFSS [8]. Figure 1 shows the configuration and scattering parameters of the short-slot hybrid coupler with a matched H-plane impedance linear taper. The short-slot hybrid coupler with one taper obtains 27 % bandwidth: amplitude imbalance of < 1 dB, input return loss of < -19 dB and isolation of < -19 dB. The simulated electric field pattern of the one-stage linear tapered coupler is shown in Fig. 2. There are concerns about the mechanical strength of this design, since a very thin 0.08 mm wide septum is required. Thicker septa are preferred from a fabrication point of view. When a septum of 0.3 mm width is employed in this tapered coupler, the bandwidth is reduced to 12 % due to a worse impedance matching which degrades the amplitude imbalance.
Fig. 3 shows the geometry and scattering parameters of a two-stage linear tapered coupler. This coupler bandwidth is as wide as 32% with the following performance: amplitude imbalance of $\leq 1$ dB, input return loss of $<-15$ dB and isolation of $<-15$ dB. Although the return loss and isolation are deteriorated to $<-15$ dB, this coupler provides a performance at least as good as the previous coupler with a thin septum, which makes it suitable for operation in a balanced mixer. Our simulations with HFSS include internal radii of 0.5 mm due to the end-mill. This radius is almost as large as the length of the first-stage linear taper and this needs to be considered in simulations. Figure 4 shows the simulated electric field pattern of the two-stage linear tapered coupler.

2.2 Fabrication

The two-stage linear tapered coupler with a 0.3 mm-wide septum was fabricated to demonstrate its performance experimentally. The short-slot hybrid coupler was made by direct machining in copper and the coupler was then gold plated. This method has the advantages of low production cost and short production time. In a split-block configuration, the waveguide structure is usually cut along the center of the E-plane (broad walls of the waveguide) where currents are theoretically zero, so as not to interrupt currents associated with the TE$_{10}$ mode. However, this short-slot hybrid coupler must be cut along the narrow walls of the waveguide to ease fabrication. This cut can potentially disturb the current flow in the waveguide if the mechanical contact between the two split-blocks is poor. The coupler

![Fig. 1](image1.png)

**Fig. 1** H plane cross-section view and scattering parameters of the one-stage linear tapered coupler. Design parameters are $L_1=1.48$ mm, $L_2=1.46$ mm, $L_3=2.86$ mm, $W_0=2.54$ mm, $W_1=4.04$ mm and $d=0.08$ mm.

![Fig. 2](image2.png)

**Fig. 2** Electric field pattern of the H plane cross-section view of the designed one-stage linear tapered coupler at 100 GHz.
is split at the edge of the narrow walls of the waveguide to reduce the loss resulting from the misalignment of the two split blocks. Figure 5 shows the diagram of the short-slot hybrid coupler split in two blocks. We took care to ensure a good contact between the two blocks at the edge of the narrow walls of the waveguide by carefully arranging 16 screws. The coupler outputs are H-plane bends for easier connections with other waveguide components. Figure 6 shows a photograph of the fabricated short-slot hybrid coupler.

2.3 Measurement

The performance of the short-slot hybrid coupler was measured by an Agilent E8361C Vector Network Analyzer (VNA) with a frequency extension module for the frequency range 80-110 GHz. Results are compared to simulation results in Fig. 7. The amplitude imbalance between the two output ports is ≤ 1 dB, and the phase difference between the output ports with respect to 90° < 3°, the input return loss is < −15 dB and the isolation is < −15 dB in the frequency range 85-110 GHz. The measured transmission and coupling include about −0.6 dB of flange mismatch and conductor loss [9]. The coupling occurs at lower frequencies than theoretically expected. From this frequency shift, we estimated the width of the septum to be around 30 μm smaller than the design value. In spite of the large fabrication tolerance due to inexpensive fabrication techniques, the design turned out to be pretty robust and only a small frequency shift.

**Fig. 3** H plane cross-section view and scattering parameters of the two-stage linear tapered coupler. Design parameters are L₁=0.49 mm, L₂=2.83 mm, L₃=1.32 mm, L₄=2.92 mm, W₀=2.54 mm, W₁=2.15 mm, W₂=3.96 mm and d=0.3 mm.

**Fig. 4** Electric field pattern of the H plane cross-section view of the designed two-stage linear tapered coupler at 100 GHz.
was detected. In the case of thinner septa, this tolerance would be unacceptable and much more expensive fabrication processes would be required.

2.4 A Scalable and Machinable Design

The proposed two-stage linear tapered coupler has a septum that is more than four times thicker than that used in a one-stage linear tapered coupler, which considerably eases the fabrication of the coupler for high-frequency designs. The compact split-block design is well suited to direct machining in copper. The design as presented for W-band can be scaled to 500 GHz with little difficulty in direct machining. At 1 THz, a too thin ~30 μm wide septum would be necessary. A three-stage linear tapered coupler would have a septum that is thicker than that used in a two-stage linear tapered coupler. Therefore, slight modifications in the design and re-optimizations should yield machinable designs with acceptable performance even up to 1 THz.

3 A Balanced SIS Mixer Using the Short-slot Hybrid Coupler

The designed short-slot hybrid coupler has been used in a balanced SIS mixer to demonstrate its performance at millimeter wavelengths. The designed balanced mixer consisted of the
presented short-slot hybrid coupler, two SIS mixers and a 180° IF hybrid. The SIS mixers presented single-ended noise temperatures averaged over the 4-8 GHz IF bandwidth below 34 K with an LO of 90-115 GHz. The gain difference between them is within ~2 dB at LO frequencies in the range of 90-115 GHz. A commercial 180° IF tapered hybrid for 4-8 GHz was used to combine the outputs of both mixers in a balanced configuration. We evaluated the performance of the 180° IF hybrid at room temperature with a VNA. Amplitude imbalance and phase difference are < 0.8 dB, and < 4° at 4-8 GHz. The mixer performance has been measured at an operating temperature of 4 K using a Joule-Thompson refrigerator. Measurements were conducted as presented in Fig. 8 using the standard $Y$-factor method [10] with room temperature (295 K) and liquid-nitrogen-cooled (77 K) black body loads. The signal from hot and cold loads was switched by a mechanical chopper. The absorber in the chopper is used as the hot load. The LO source is a W-band Gunn oscillator in the 90-115 GHz band. The bias polarities of the two SIS mixers are the same and the RF signal through

![Fig. 7 Measurement results (solid lines) and simulation results (dashed-dotted lines) for the short-slot hybrid coupler for (a) the transmission $S_{21}$ and the coupling $S_{31}$, (b) phase difference between ports 2 and 3 (c) the input return loss $S_{11}$ and the isolation $S_{41}$, (refer to Fig. 3 for port numbers).]
the balanced mixer is output from the Λ port of the 180° IF hybrid. The LO sideband noise accompanying the LO signal is removed into the Σ port of the 180° IF hybrid [11]. Each output is amplified by a low-noise InP-HEMT amplifier with a noise temperature of 5 K.

Bias of mixer A was fixed, while bias of mixer B was swept, and then the balanced mixer was optimized to the minimum noise temperature. Figure 9 shows the measured current-voltage characteristics of mixer B of the balanced mixer with and without LO power at 100 GHz. The averaged IF responses over the 4-8 GHz to hot and cold loads as a function of bias voltage are also shown. The maximum Y-factor was 4.9 dB corresponding to receiver noise temperature of 29 K at a mixer bias of approximate 14 mV. The LO frequency dependence of the noise temperature of mixer A, mixer B, and the balanced mixer is shown together in Fig. 10. It should be noted that the noise temperature excluded the thermal noise from the LO port, inserted from the –20 dB coupler, since the LO source was at room temperature.

The performance of the balanced mixer was close to that of the single-ended mixers on which it was based.

Fig. 8 Block diagram of a balanced mixer. The balanced mixer consists of short-slot hybrid coupler, two SIS mixers, and 180° IF hybrid.

Fig. 9 I - V characteristics and heterodyne responses of the balanced mixer with hot and cold loads at LO frequency of 100 GHz and over the IF 4-8GHz.
The isolation of the balanced mixer depends on the amplitude and phase balance of the different components. The LO sideband noise rejection ratio (LNR) has been defined to express the performance of the balanced mixer [12]. The LNR was simply estimated by the quotient of the conversion losses measured at the two IF output ports [13]. The average LNR at the measured LO frequencies between 90 and 115 GHz was more than 11 dB. This is consistent with theoretical estimations considering a short-slot hybrid coupler imbalance of 1 dB, a mixer gain imbalance of around 1 dB, a 180° IF hybrid imbalance of 0.8 dB, and an overall phase error at the summing node of 10 degrees. These results suggest that our proposed short-slot hybrid coupler works well in W-band at 4 K.

4 Conclusion

We have designed a short-slot hybrid coupler using two-stage linear tapers for application at millimeter wavelengths that can be fabricated using low-cost techniques. The main advantage of this coupler with respect to existing ones is that the design is very simple and it can be manufactured at low cost, even for high-frequency use up to sub-millimeter wavelengths. Simulations of this short-slot hybrid coupler show amplitude imbalance between the two output ports of \( \leq 1 \) dB, phase difference between the output ports with respect to \( 90^\circ < 3^\circ \), input return loss \( < -15 \) dB, and isolation \( < -15 \) dB in the frequency range 85-117 GHz. The fabricated short-slot hybrid coupler was measured by a VNA at room temperature. The results showed small amplitude imbalance and phase shift difference between the output signals as expected from theoretical considerations across the measured frequency range of 85-110 GHz.

The short-slot hybrid coupler was used in a balanced SIS mixer at 4 K. The performance of the balanced mixer was very close to that of the single-ended mixer on which it was based. These results indicate that our short-slot hybrid coupler has great potential for practical millimeter- and submillimeter-wave applications.

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