A Planar Beam Splitter for Millimetre and Sub-Millimetre Heterodyne Mixer Array

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***Abstract*—We present the design of a four-port planar circuit beam splitter comprising a microstrip and a coplanar waveguide (CPW) crossing each other. The CPW is fabricated in the ground plane (bottom layer) and the microstrip is deposited on top of the dielectric layer. A small section of the microstrip line is bent and aligned parallel to the central conductor of the bottom CPW, allowing the level of power coupling to be easily controlled by changing the length of the aligned section. The simple layout of the planar beam splitter makes it easy to fabricate in a wide frequency range from microwave to sub-millimetre (sub-mm) wavelengths. In this paper, we describe in details the electromagnetic design of the planar beam splitter and its predicted performances in the frequency range of 600–700 GHz. We discuss the potential usage of the planar beam splitter as a replacement to the free-space beam splitter in receivers, in particular those using superconductor-insulator-superconductor (SIS) mixer arrays. To investigate the integrity of our design in a controlled way we scaled the design to operate in the Ku-band and measured the performance of several prototypes experimentally. Our tests showed good agreement between the measured performance and simulations.**

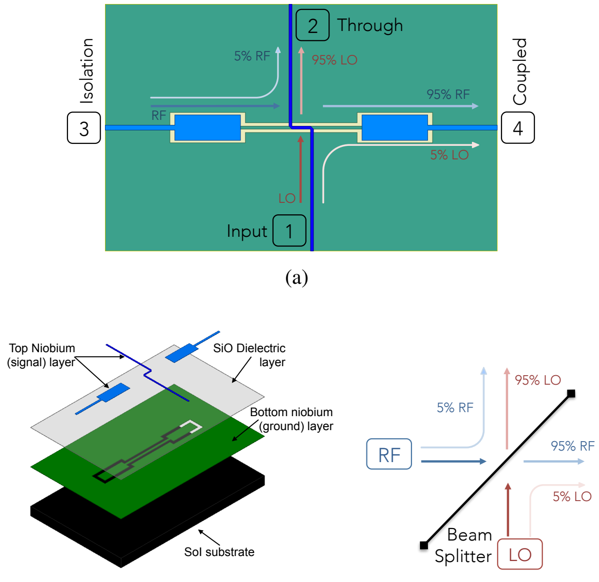
***Index Terms*—Coupling circuits, Power distribution lines, Superconducting integrated circuits, Submillimeter wave technology, Radio astronomy**

I. Introduction

THE time available for astronomical observations at short sub-millimetre (sub-mm) wavelengths is limited even at high dry sites such as the Atacama desert or the South Pole. The situation is even more challenging in sub-mm heterodyne observations, since most of the existing sub-mm receivers have only one pixel in the focal plane. It is therefore important to replace the single-pixel receiver with a large focal plane array in order to maximise the scientific returns within the available time of observation. However, key technologies required to build heterodyne receivers with large number of pixels at high frequencies are still challenging [1]. It requires innovative technology development such as compact LO injection scheme [2], modular array design that is easily extendable [3] and highly integrated IF amplifiers [4].

One of the major challenge in constructing a compact focal plane array is that there are only two interfaces in each mixer element shared between the three mixer signals i.e., the LO, RF and the IF ports. In order to feed the LO power to each mixer element from a single source, the LO path needs to bypass the RF path to reach the next element with negligible loss (apart from the coupled power). Traditional millimetre and sub-mm heterodyne arrays solve this problem by using either multiple split blocks with a large waveguide coupling network [5], series of free-space beam splitters [6] or LO beam multiplexing [7] where the RF and LO signals are combined and injected at the mixer's input port. These solutions are bulky and complicated to fabricate. Furthermore, the available LO power is not fully harnessed, which is crucially important at high-frequencies where the LO power from a single source is limited.

In this paper, we describe a fully planar planar beam splitter



(a)

(b) (c)

Fig. 1. (a) A sketch showing the power distribution between the two transmission paths of a planar beam splitter. (b) 3-D view of the beam splitter showing the different layers making up the device. Both the top and bottom niobium layers are 400 nm thick, with the silicon monoxide (SiO) dielectric layer at 475 nm. The entire planar circuits are deposited on a 15 μm thick SoI substrate. (c) Power transmission characteristics of a traditional dielectric beam splitter.

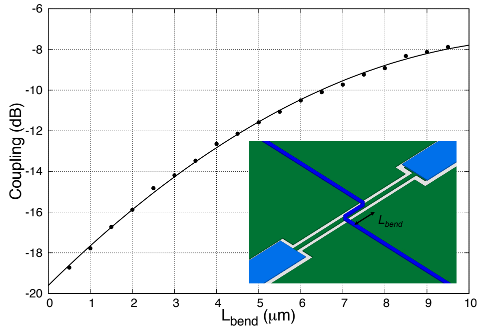


Fig. 2. The relation between the length of the Z-bend section and the level of power coupling between the two transmission lines simulated using Ansys HFSS at 650 GHz.

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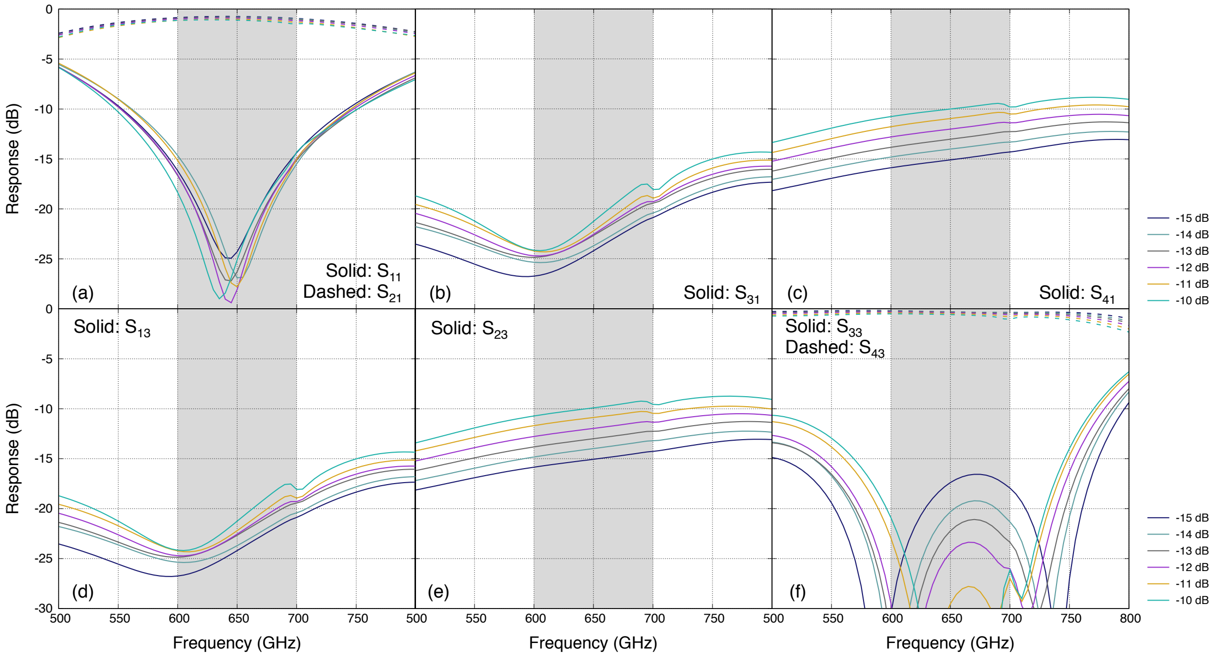


Fig. 3. The HFSS simulated S-parameters for a set of six planar beam splitters, with the coupling coefficient ranging from –15 to –10 dB. The top row shows the power relations between the four ports from the input port 1, while the bottom row shows the similar power relations from the isolation port 3. The shaded area represents the design frequency bandwidth.

design that can be used to replace these traditional approaches. It is compact, easily scale-able from microwave to terahertz frequencies, and can be integrated directly into the mixer circuits. This will not only eliminate the need for extra optical components to carry the free-space beam splitter, or the bulky waveguide network, but will also reduce the cryogenic and space requirements considerably, hence paving the way to the construction of a large kilo-pixel heterodyne receivers.

II. DESIGN

The planar beam splitter is an assembly of two planar circuit transmission lines fabricated on the opposite sides of a dielectric layer and crossing each other as shown in Fig. 1. One of the transmission lines is a microstrip (hereinafter TL_1) constructed on the top superconducting layer, while the other transmission line is a coplanar waveguide (CPW) fabricated in the ground plane (hereinafter TL_2). The bottom CPW is then transformed back to microstrip via a pair of broadside couplers, so that all the ports are located on the top layer, and can be integrated easily with the commonly used microstrip-based circuits. The length of the bottom CPW (the distance between the two broadside couplers) is about half a wavelength at the band-central frequency, and the length of the broadside couplers is approximately half that. The width and gap of the broadside couplers were chosen to minimise the impedance mismatch between the bottom CPW and the top connecting microstrip. The impedance of all microstrip ports was set to 20 Ω (microstrip 3 μm wide), compatible with the normal resistance of our 1 μm^2 tuned superconductor-insulator-superconductor (SIS) junction. The structure is fully planar with clearly separated layers, easy to fabricate, with the entire circuit deposited on a thin silicon-on-insulator (SoI) substrate. The design of the planar beam splitter was optimised using the electromagnetic simulator, Ansys HFSS™, across the required bandwidth.

The planar beam splitter design is similar to a CPW-CPW crossover reported in [8]. In that design, the field lines of the CPWs where the signals pass through the device are transverse to the other, hence preventing power leaking from one transmission line to the other during the cross over. In our case however, we have modified the design by firstly replacing the top CPW with a microstrip, to allow a small amount of power to be coupled between them. Secondly, a section of the top microstrip was bent and aligned with the central conductor of the bottom CPW (hereinafter the Z-bend section) to increase the power coupling. An important feature of this alteration is that the inter-arm power coupling is directional i.e., the power from the input port of TL_1 (port 1, input) only couples to the output port of TL_2 (port 4, coupled), but not the input port (port 3, isolation). This behaviour is exactly the same as the traditional dielectric beam splitter, as shown in Fig. 1(c).

A key feature of the planar beam splitter design is that the coupling coefficient can be controlled easily by altering the length of the Z-bend section without changing other geometries of the circuit. This is illustrated in Fig. 2 which shows that the level of power coupling between the two transmission lines increases approximately exponentially with the length of the Z-bend. This feature is especially useful for constructing an LO distribution network that needs to divide the input LO power evenly between a series of mixers in an array. In particular, the drop of input power after each beam splitter can be compensated for, by gradually increasing the Z-bend length, ensuring the LO power delivered to all mixers remains constant. By cascading the beam splitter in series, the power that passes through each splitter suffers only a small coupling loss and the remaining power can be fed to the next device, hence utilising all the available LO power.

Fig. 3 shows the simulated results of a set of six planar beam splitters designed to operate from 600–700 GHz, each with the coupling strength ranging from –10 to –15 dB. The return losses of both input ports (port 1 for the LO and port 3 for the RF signals) are well below –15 dB, with the transmission coefficient close to –1 dB for both transmission lines (see panel (a) and (f)). The isolation for both input ports is also low, less than –20 dB across the designated bandwidth for the six designs. The coupling coefficients for both transmission lines are exactly the same (since the splitter is a reciprocal device), with the coupling behaviour of all six designs almost identical and clearly separated by 1 dB apart as designed. Note also that both sets of the transmission coefficients remain flat and almost unchanged even when the coupling coefficient is increased from –15 dB to –10 dB. Similarly, the isolation and return loss are also relatively unaffected.

III. A 1×4 SIS MIXER ARRAY

To demonstrate the feasibility of the method of power cross-coupling described above in conjunction with SIS mixers, we designed a 1×4 SIS mixer array with the beam splitters integrated on-chip with mixers and their ancillary planar circuits. Here the beam splitter is used as a cross coupler to combined the LO and RF power and feed them to the mixer device. All the superconducting planar circuit components are deposited on a 15 μm thick SoI substrate, with gold beam leads for ground connections as shown in Fig. 4. The LO power is fed to the array via a finline antenna on the left and delivered to each SIS mixer through its own planar beam splitter. The transmitted power through the array exits the chip via a radial probe antenna. Each pixel comprises an SIS finline mixer fed by a planar beam splitter and the corresponding input antenna. The finline antenna and the mixer circuit is similar to the wide RF/IF bandwidth design we have reported previously [9]. It is worthwhile noting that the broadside couplers employed in the beam splitter device also act as DC-blocks for each mixer element, allowing the mixers to be DC-biased separately, without cross-talk between the pixels.

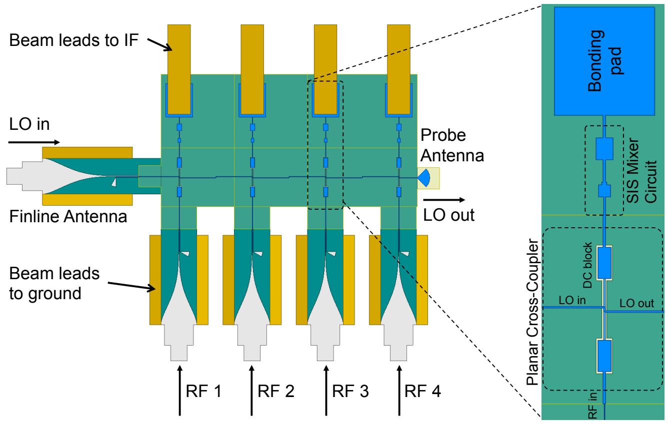
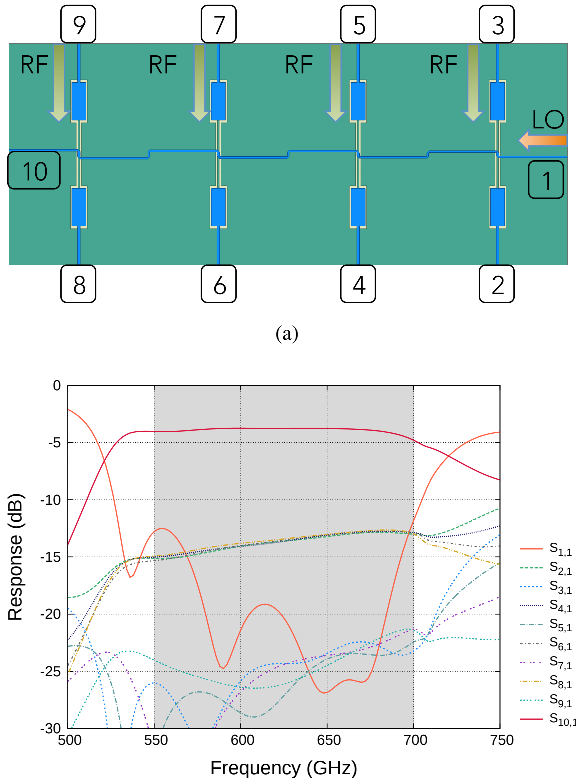


Fig. 4. Planar 4-pixel SIS mixer array chip with integrated planar beam splitters and mixer circuits deposited on a 15 μm thick SoI substrate. The top and bottom superconducting layers are modelled as 400 nm thin niobium superconductor, with a dielectric layer of silicon monoxide at 475 nm.

Fig. 5(a) shows the zoom-in view of the 4-pixel planar beam splitters cascaded in series. The LO port is denoted as port 1, while the four RF input ports are numbered as port 3, 5, 7 and 9. The SIS mixer for each branch is connected to the beam splitter array via port 2, 4, 6 and 8. The remaining LO power exit through port 10. To ensure that the LO power is distributed evenly between the mixer branches of the array, the Z-bend length is gradually increased to compensate for the drop of the input LO power after each branches. As shown in Fig. 5(b), the LO power coupled to all the four mixer branches stays constant at exactly the same strength across the 550–700 GHz band. The isolation leakage is near –25 dB and the return loss as low as –20 dB across the same bandwidth.

Notice that the remaining LO power after passing through the four SIS pixels array is still strong at $S_{10,1} = -4$ dB, and is flat across the operating frequency range, hence it can still pump many more mixers. This can be done either by cascading more mixers in series or using the modular nature of the array chip to stack them above each other, each in a mixer block, forming an $n \times 4$ compact array. To feed all array layers with a single LO source, the LO power could be passed from one array level to the one above it via the radial probes at the end of the array chips. The two probes, one from each array chip along with the rectangular waveguide backshorts, form a back-to-back coupling antennas that enable maximum LO power coupling between layers [10].



(a)

(b)

Fig. 5. (a) Zoom-in view of four planar beam splitter cascaded in series, and the port annotations. (b) The response of each output port in relation to the LO port. Note that the LO power coupled to all the mixer ports ($S_{2,1}$, $S_{4,1}$, $S_{6,1}$ and $S_{8,1}$) is identical from 550–700 GHz.

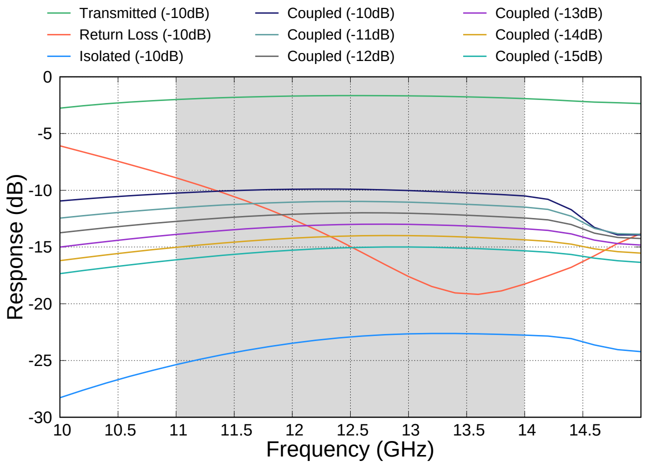
IV. SCALE MODELS NEAR KU-BAND

In order to verify the integrity of the planar beam splitter design, we scaled all the six single-pixel designs down from 650 GHz to operate at ∼13 GHz. This allows full S-parameters characterisation of the device using a vector network analyser (VNA) and quick modification of the parameters which is much harder to achieve in the cryogenic environment of sub-mm mixers. Fresh electromagnetic simulations of the chip at the scaled frequencies were made to compare with measured results.

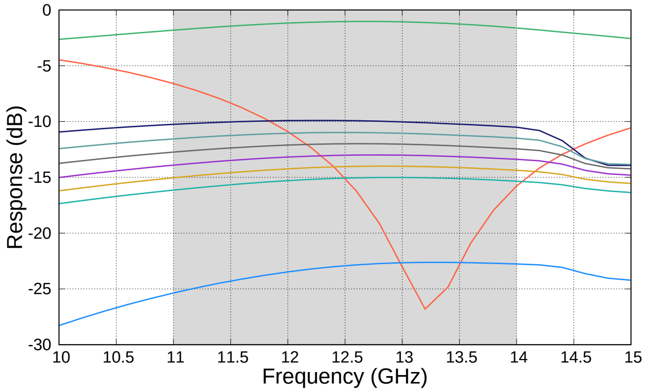
Fig. 6 shows a photograph of one of the assembled prototypes. The beam splitter circuits were fabricated on both side of a 10-mil thin Roger RO4350™ printed circuit board (PCB, $\epsilon_r = 3.66$), supported by a thicker Roger Duroid 6010 bare substrate (1.27 mil, $\epsilon_r = 10.9$) to emulate the effect of the SoI substrate in SIS mixers. All the microstrip ports were set to 50 Ω, compatible with the SMA connectors (GigaLane panel edge mount PCB connector PSF-S05-000). The size of the entire fabricated test device is about 27 × 27 mm, limited mainly by the size of the SMA connectors. Since the ground plane of the beam splitter circuit is sandwiched between the thin RO4350 PCB and the Duroid 6010 substrate, vias were created to electrically connect the bottom ground plane to the top layer.

Fig. 7 shows the predicted performances of the scaled models simulated using HFSS, with the coupling coefficients ranging from –10 to –15 dB (in 1 dB steps). It can be seen that the expected performance is broadband, with isolation well below –20 dB for both TL$_1$ and TL$_2$, in the frequency range 11–15 GHz (approximately 30% bandwidth). In particular, the power coupling between the two transmission lines remains constant in the same frequency range. In summary, the simulations at 13 GHz turned out to be a scaled version of the simulations at 650 GHz which is to be expected for a passive component.

The S-parameters behaviour of all four ports of the scaled models were measured simultaneously using the Rohde & Schwarz ZNB 20 VNA. The results for the six prototypes are summarised in Fig. 8. It can be seen that the measured return loss for both transmission arms is below –15 dB from 12–14 GHz, and the isolation is close to –20 dB across the entire 11–14 GHz band. These results agree very well with simulation as can be seen by comparing Fig. 8, with Fig. 7. The closely separated coupling levels for the six prototypes can clearly be identified and remain relatively flat across the band. Next we tested the dependence of the coupling coefficient on the length of the Z-bend. The behaviour is shown in Fig. 9, where the measured coupling coefficients of both S$_{4,1}$ and S$_{2,3}$ at the band centre agrees very well with simulated curve, with the coupling responses increased approximately exponentially with the Z-bend length as simulated.



(a) Port 1 (TL$_1$'s input)



(b) Port 3 (TL$_2$'s input)

Fig. 7. Simulated transmission, return loss, isolation and coupling coefficients from (a) the input port (1) of the first transmission line (TL$_1$, microstrip), and (b) the input port (3) of the second transmission line (TL$_2$, CPW). The legends are the same for both plots.

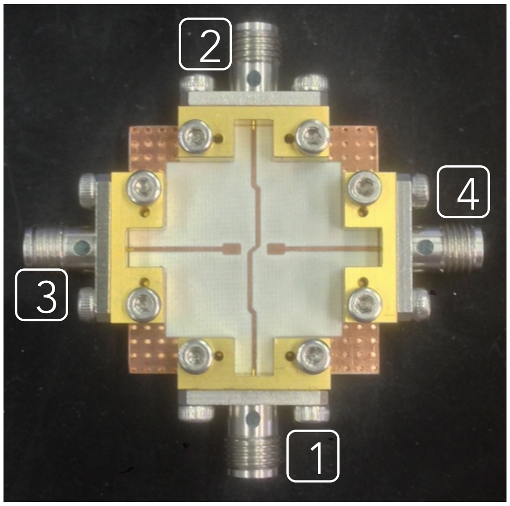
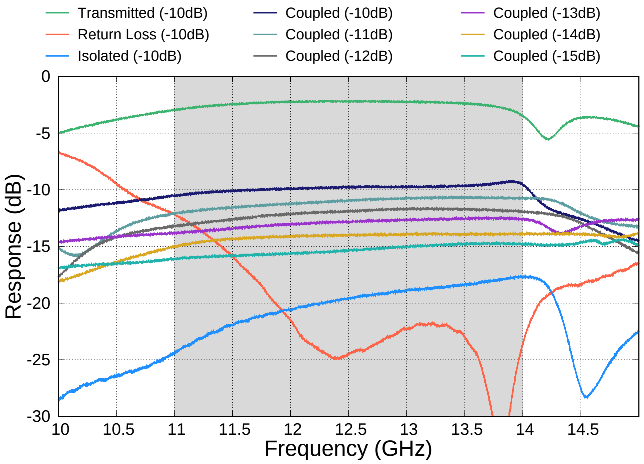


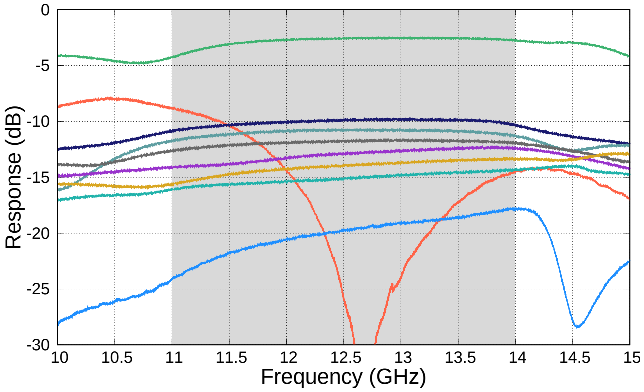
Fig. 6. Photograph of one of the assembled scaled model prototype.

V. CONCLUSION

We have presented the design of a planar beam splitter which have the same power transmission behaviour as the optical thin dielectric film beam splitter. It comprises a microstrip-CPW transmission lines pair, crossing each other at 90°. A small section of the top microstrip (fabricates in the top layer) is bent and aligned with the CPW (fabricated in the ground plane) to control the power coupling between the two transmission arms. This allowed us to design six beam



(a) Port 1 (TL$_1$'s input)



(b) Port 3 (TL$_2$'s input)

Fig. 8. The measured transmission, return loss, isolation and coupling coefficients from (a) the input port (1) of the first transmission line (TL$_1$, microstrip), and (b) the input port (3) of the second transmission line (TL$_2$, CPW). The legends are the same for both plots.

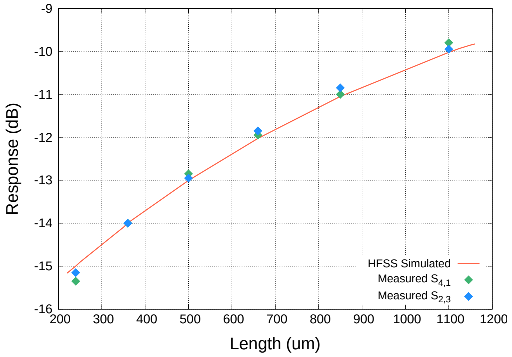


Fig. 9. The measured relation between the length of the Z-bend section and the level of power coupling between the two transmission lines at the band centre 12.5 GHz.

splitters at 650 GHz, each with different coupling level and yet all had broad band performance. We have also shown how to implement this technology to simplify greatly the LO and RF power combination path in sub-mm SIS mixer arrays, by replacing the traditional free-space beam splitter with the planar circuit version integrated directly on the mixer chip. In order to verify the design feasibility of the planar beam splitter in a controlled manner, we have scaled down the design and fabricated a set of six prototypes to operate in the Ku-band. The measured performance was excellent, agreeing very well with the simulated predictions. Although the examples given in the paper focused on the SIS mixer architecture, the technology is well suited for other superconducting detectors circuits that requires optical beam splitter such as hot electron bolometers and Schottky mixers. We believe that the planar beam splitter will pave the way to make the construction of a kilo-pixel heterodyne array feasible in the near future, in particular around the THz region.

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