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RESEARCH PAPER

Technology developments for a large-format heterodyne MMIC array at W-band

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We report on the development of W-band (75–110 GHz) heterodyne receiver technology for large-format astronomical arrays. The receiver system is designed to be both mass producible, so that the designs could be scaled to thousands of receiver elements, and modular. Most of the receiver functionality is integrated into compact monolithic microwave integrated circuit (MMIC) amplifier-based multichip modules. The MMIC modules include a chain of InP MMIC low-noise amplifiers, coupled-line bandpass filters, and sub-harmonic Schottky diode mixers. The receiver signals will be routed to and from the MMIC modules on a multilayer high-frequency laminate, which includes splitters, amplifiers, and frequency triplers. A prototype MMIC module has exhibited a band-averaged noise temperature of 41 K from 82 to 100 GHz and a gain of 29 dB at 15 K, which is the state-of-the-art for heterodyne multichip modules.

Keywords: Hybrid and Multi-chip Modules, Low Noise and Communication Receivers

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I. INTRODUCTION

Large-format monolithic microwave integrated circuit (MMIC) heterodyne arrays, with hundreds to thousands of receivers, have many exciting applications in millimeter-wave astronomy. Examples of science that would be enabled with these arrays include:

– Probing the process of star formation in galactic molecular gas clouds by mapping gas-tracing spectral lines.
– Mapping low surface brightness emission, such as large-scale structure, with existing millimeter-wave interferometers (e.g. CARMA [1]) that could be enhanced with small focal plane arrays on each telescope that would increase the field of view.
– Exploring the history of the early universe via measurements of the polarization of the Cosmic Microwave Background with a short-baseline interferometer [2].
– Examining the expansion rate of the universe by mapping the Sunyaev–Zel'dovich Effect in galaxy clusters with large-format interferometers.

The requirements for all of these applications are similar: low noise, large bandwidth (≥15 GHz), and a large number of receiving elements (typically hundreds to thousands).

Previous instruments have already demonstrated the utility of hand-built cryogenic MMIC heterodyne arrays with just tens of elements (e.g. SEQUOIA [3]). The focus of the work presented here is to develop cryogenic heterodyne receivers whose assembly techniques are amenable to the fabrication of much larger arrays. The use of MMIC technology allows for all of the receiver components to be integrated into a single compact package, or MMIC module, that is easily mass-producible (see e.g. [4]). The MMIC module interfaces were chosen to maximize modularity so that malfunctioning receivers can be easily swapped. Multilayer boards provide a cost-effective way to route a high density of signals to and from the MMIC modules. The technology presented here will be implemented into a 4-pixel proof-of-concept subarray, which is currently under construction.

The integrated MMIC heterodyne module discussed herein has demonstrated record noise temperature at W-band of 41 K over a wide bandwidth (82–100 GHz). The previous state-of-the-art for W-band MMIC heterodyne systems was SEQUOIA, which quotes a 50–80 K noise temperature over the 85–115.6 GHz band [3]. However, that design was not fully integrated. Other fully integrated W-band heterodyne receiver modules have been presented in the literature [5, 6, 7, 8], but cryogenic noise data were not reported.

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This paper is organized as follows: the MMIC module design is presented in Section II, a description of the chipsets is given in Section II(C), the MMIC module performance is summarized in Section III, and the design and performance of the multilayer signal-routing boards are shown in Section IV along with the 4-pixel sub-array concept. This work was presented in less detail at the European Microwave Conference [9].

II. MMIC MODULE DESIGNS

Two W-band heterodyne MMIC module designs are presented: a single-sideband (SSB) receiver and a double-sideband (DSB) I-Q receiver. The SSB receiver was designed as a proof-of-concept for a large-scale cosmic microwave background interferometer [2], while the DSB receiver is intended for spectroscopy and builds upon previous work [10].

Both modules include a chain of InP MMIC low-noise amplifiers (LNAs), followed by a sub-harmonic Schottky diode mixer, which downconverts the RF signal to the intermediate frequency (IF) band. The RF input to the modules is WR-10 waveguide, which has a nominal frequency range of 75–110 GHz, but in practice does not become over-moded until 118 GHz. A waveguide-to-microstrip transition [11] precedes the LNAs and planar filters located after the LNAs provide band definition. The chips are described in detail in Section II(C) and their gain contributions to the MMIC modules are summized in Table 1.

The component chips are epoxied[1] into 0.381 mm cavities in a base block made from gold-plated brass (see Fig. 1) with a lid (not shown) that forms an RF-tight seal. The components are interconnected via gold ribbon wire bonds. While these MMIC receiver modules were both hand assembled, their split-block design is conducive to future automated assembly.

The LNAs and mixer are biased by means of hermetic feed-through pins[2] that connect to a printed circuit board (PCB) with bias circuitry on the reverse side of the block. A nano-miniature nine-pin strip connector provides an easy means of connecting and disconnecting the bias lines.

A) SSB module

The SSB prototype receiver module was designed for operation at a fixed local oscillator (LO) frequency of 40 GHz with instantaneous RF bandwidth from 82 to 100 GHz. The second harmonic mixer downconverts the RF signal to a 2–20 GHz (IF) band. The LO and IF interface is achieved through standard 1.85 and 2.92 mm coaxial connectors[3] which were chosen for ease of testing the prototype. The SSB MMIC module also includes an LO phase shifter, which would be required for interferometric operation.

B) DSB module

The DSB MMIC module was implemented using an I-Q configuration, which allows for the downconversion of larger bandwidths at the expense of having to route twice as many IF signals. The I-Q downconversion is implemented with separate second-harmonic mixer chips for the in-phase and quadrature outputs. The LO signal is split and a 45° phase shift is introduced between the two signals before they reach the mixers. The requisite Wilkinson splitters and phase delays were patterned on alumina. The DSB MMIC module is intended to have a 45 GHz LO signal and accepts RF frequencies in the 75–105 GHz range. Miniature push-on connectors (Section IV(c)) were used for the IF and LO in order to enhance modularity and compactness.

Table 1. Approximate gain contributions for individual components in the MMIC modules.

Component	Expected gain (dB)	
	SSB module	DSB module
Waveguide-to-microstrip transition	−0.5	−0.5
LNA 1	20–29	10–15
LNA 2	20–29	10–15
Filter	−1.5	−1.5
LNA 3	N/A	20
Mixer	−12 to −20	−15 to −23
Total module gain	20–38	15–33

The component data are given in [11, 12, 13, 14].

C) Chip sets

1) LOW-NOISE AMPLIFIERS

The sensitivity of the MMIC modules is dominated by the noise contribution of the low-noise amplifiers. The SSB module has two four-stage 100 nm gate length InP MMIC LNAs [12] that were fabricated by Northrop Grumman Corporation and were also used in the QUIET experiment [4]. The DSB module implements newly developed two-stage 35 nm gate length InP MMIC LNAs [13], which have improved noise properties. Cryogenic noise measurements for this LNA in a waveguide package are shown in Fig. 2 with details of the testing given in Section III. The 35 nm devices have typical room temperature gains of 10–15 dB across the 75–105 GHz band as described in [13]. The gain at cryogenic temperatures is expected to be roughly the same. A third LNA is required in the DSB module in order to avoid significant noise contributions from the mixer and IF amplifiers. A three-stage InP MMIC LNA with higher gain (18–20 dB across the 70–140 GHz band) [14] was utilized for this.

2) MIXERS

Both modules incorporate the same second-harmonic Schottky diode mixer (the DSB module uses two), which has a conversion loss of 12–20 dB. The LO signal for this mixer is sub-harmonically pumped at 40 GHz (SSB module) or 45 GHz (DSB module). It is possible to generate and route this signal much more efficiently than the 80 or 90 GHz signal that would be needed for a fundamental mixer. The mixer is the bandwidth limiting component for both MMIC modules.

3) FILTERS

The receiver modules include four-pole coupled line bandpass filters, which were implemented on 0.1 mm alumina substrate.

[1] EPO-TEK H20E Silver Epoxy.
[2] Thunderline-Z TL1946.
[3] Anritsu V102F-R & K102F-R.

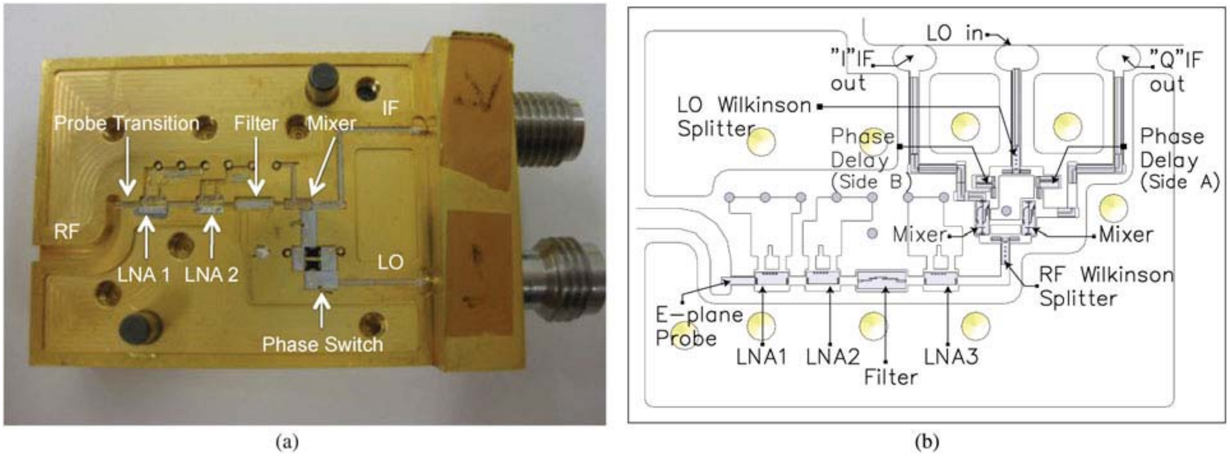

Fig. 1. (a) Photograph of the SSB prototype MMIC module with the component chips labeled. Shown are the w>aveguide-to-microstrip transition, MMIC low-noise amplifiers, Schottky diode mixer, phase switch, and coaxial connectors. (b) Design drawing for the DSB MMIC receiver module. The module includes three low-noise amplifiers, a filter, an I-Q downconversion system, and miniature push-on connectors for the IF and LO.

The insertion loss is approximately 1.5 dB and the 3 dB bandwidth is 78–118 GHz. In the DSB module, the filter is between the second and third LNAs in order to minimize out-of-band loading at the third LNA and mixer. In the SSB module, the filter is responsible for sideband separation.

III. MMIC MODULE PERFORMANCE

Noise temperature and gain measurements of the SSB prototype module have been performed using the standard Y-factor technique where a variable thermal load (VTL) was implemented with a waveguide termination and heater. A piece of stainless steel waveguide provided a thermal break between the VTL and MMIC module. The physical temperature of the MMIC module was set at 15 K with a PID control loop while the VTL temperature was changed from 15 to 40 K. The IF was fixed at 1 GHz due to equipment limitations and was amplified and then measured with an Agilent E4446A PSA Spectrum Analyzer. The resulting cryogenic data are shown in Fig. 2, where the measurement reference plane is at the WR-10 input flange. An average noise temperature of 41 K and gain of 29 dB were obtained across the 82–100 GHz band.

Preliminary measurements of the DSB module over the 75–105 GHz band have shown a 39 K noise temperature and 19 dB gain. The improved performance is due to the upgraded front-end LNA, whose noise data are shown in Fig. 2. These noise measurements were also made with the VTL method described above. A more detailed description of the DSB module will be released in a future publication.

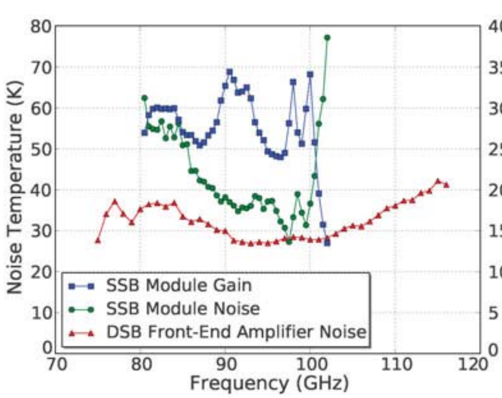

Fig. 2. Noise temperature and gain of the SSB prototype MMIC module at 15 K. The measurement was taken with the IF fixed at 1 GHz because of equipment limitations. The bandwidth is limited by the mixer performance. Also shown is the cryogenic noise temperature of a newly designed low-noise amplifier [13], which uses 35 nm gate length InP technology. This amplifier has been installed in the DSB MMIC receiver module.

IV. SIGNAL ROUTING

Routing the IF and LO signals is a major challenge for large-format receiver arrays. Coaxial cables and waveguide offer excellent broadband RF performance and isolation between signal paths, but they are bulky and cumbersome to install for large arrays. Instead, we have developed multilayer PCBs using a high-frequency laminate[4] These boards provide a very cost-effective and compact way to route large numbers of signals to and from the array.

The multilayer boards will be used to construct a 4-pixel proof-of-concept array, which could be used as a building block for a much larger array. A schematic and concept drawing of this array are shown in Fig. 3. The signal routing and processing will be carried out on two stages of multilayer boards; a 20 K board that will interface directly with the MMIC modules and a 77 K board. The 20 K board will route the IF and LO signals, split the LO signal, and triple the LO frequency and the 77 K board routes the signals and provides IF amplification. Microstrip lines using flex circuit technology will provide thermal breaks between the cryostat stages and to the room temperature cryostat walls. The multilayer routing boards were prototyped in subsections: a transition from microstrip on outer layers to stripline on interior layers, the LO splitter and multiplier, the miniature push-on connectors, and the flex lines. Each of these prototype subsections are detailed below.

[4] Rogers 4350B (0.254 mm thickness).

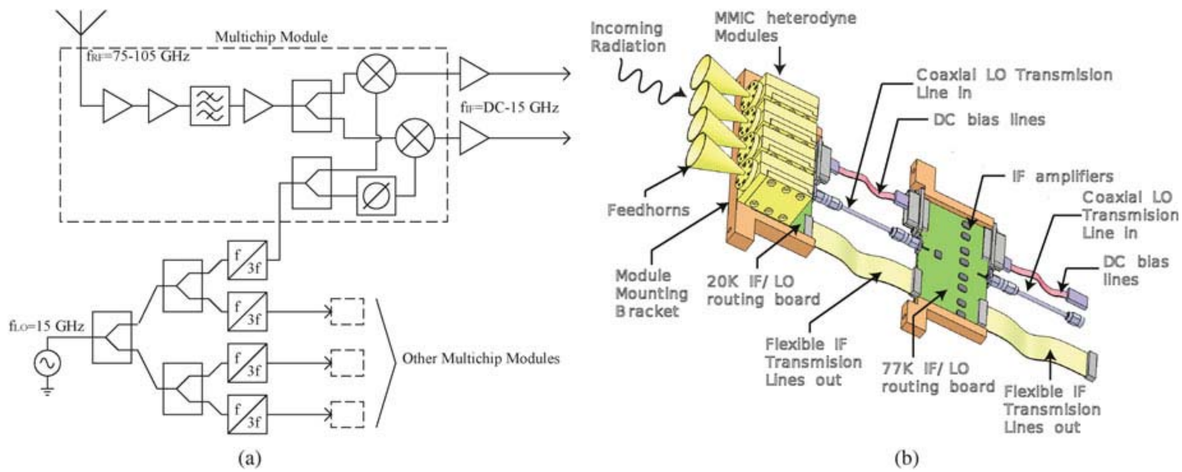

Fig. 3. (a) A schematic of the signal routing scheme. (b) A concept drawing of a 4-pixel array. Multilayer PCBs route the IF and LO signals to and from the modules, with the LO being on the top layer and the IF on an interior layer. The 20 K board will include LO splitters and frequency multipliers; it interfaces with the MMIC modules via miniature push-on connectors. Thermal breaks are implemented on flex circuitry for the IF lines and stainless steel semi-rigid cable for the LO lines.

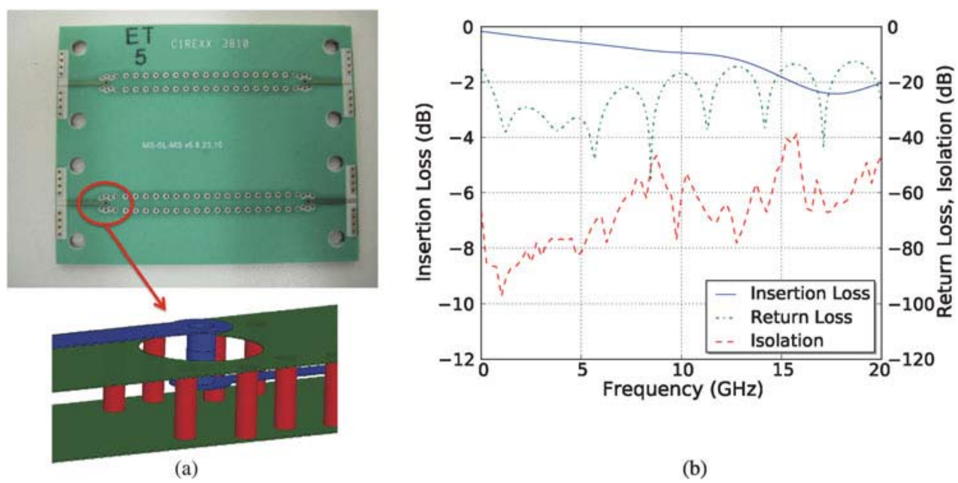

Fig. 4. The IF will be routed on an interior layer of the routing boards for improved isolation and to allow crossing of the IF and LO signals on the board. A photograph of a stripline-to-microstrip test board is shown in (a). Each line has back-to-back stripline-to-microstrip transitions, where the lines are separated by 15 mm. The total board length is 38.1 mm. The measured performance of stripline-to-microstrip test board is plotted in (b).

A) IF Routing

The IF routing was designed to accommodate not just the DC to 10–15 GHz IF signals from the MMIC receiver modules described in Section II, but also to permit the fabrication of future instruments that can cover 40 GHz instantaneous bandwidth (i.e. two 20 GHz IF signals for an I-Q system).

The IF signals have been routed on one of the interior layers of the board using stripline in order to reduce pixel-to-pixel cross-talk and to allow the IF and LO lines to cross. The stripline layer is accessed via stripline-to-microstrip transitons, which are illustrated in Fig. 4(a). These transitions employ coaxial vias [15], where the signal via is surrounded by a number of ground vias, forming a coaxial transmission line. The ground vias also function to suppress unwanted parallel plate modes that are generated at the transition and propagate through the dielectric. A wall of vias along each side of the stripline was included to further reduce cross-talk between lines. The performance of 3.8 cm test boards with back-to-back stripline-to-microstrip transisitions is given in Fig. 4(b). The test board measurements include the performance of the test connectors[5] which were the reference planes for these measurements. The worst-case return loss is 15 dB over the DC-20 GHz band. The insertion loss is less than 2.5 dB and the average isolation is 53 dB across the band with a peak of 39 dB for 15 mm spaced lines.

B) LO Routing

The LO signals will be routed on the top layer of the multilayer routing board. A 15 GHz input signal will be split four ways, tripled in frequency, and then routed to four separate MMIC modules. The frequency multiplication is performed inside the cryostat because the 15 GHz signal is subject to lower loss than its third harmonic. The LO microstrip line has a length of approximately 5 cm and a loss of 0.36 dB/cm at 16.6 GHz. A single stainless steel semi-rigid coaxial cable

[5]Southwest Microwave 1492-02A-5 and 1493-01A-5.

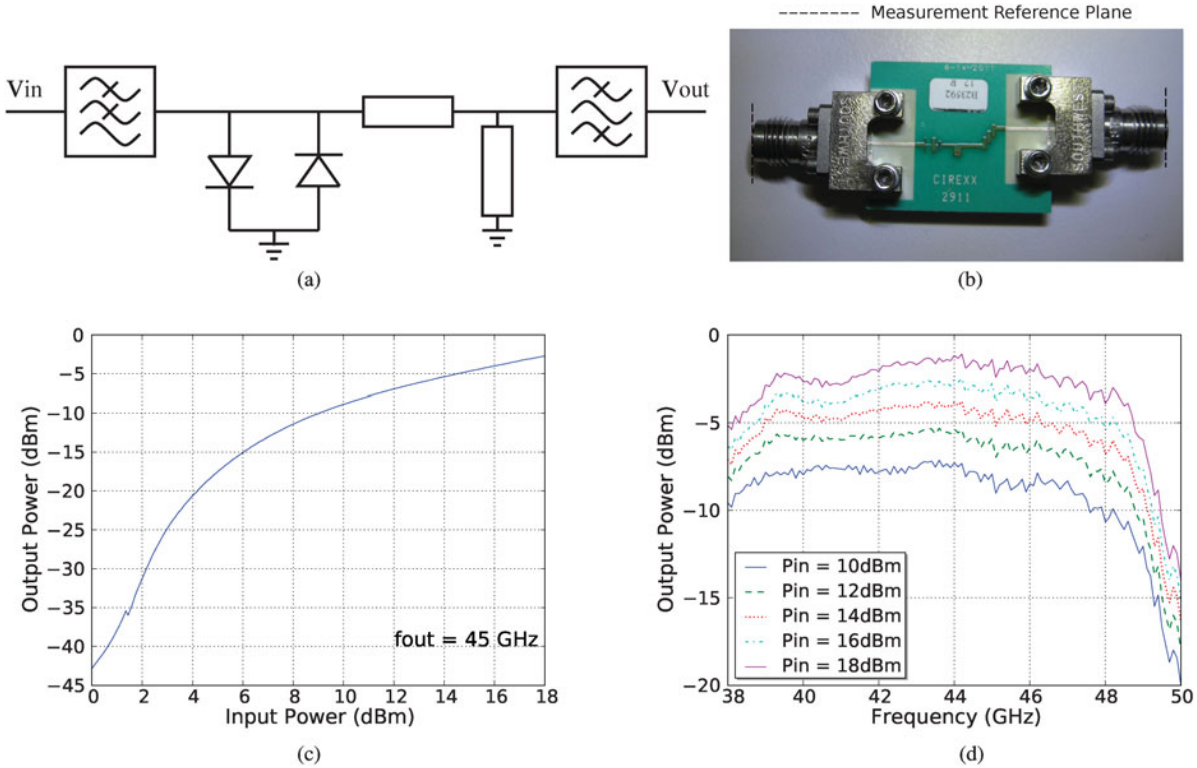

Fig. 5. (a) A schematic of the prototype frequency tripler, which utilizes a flip-chip dual diode. The input filter is a stepped-impedance design. A coupled-line filter is included as a part of the output match. (b) A photograph of a prototype test board for the diode tripler. (c) Output power versus input power with the output frequency at 45 GHz. (d) Output power versus output frequency where the input power is varied between 10 and 18 dBm in increments of 2 dBm.

will route the LO from the cryostat wall to each 20 K board, providing a thermal break as well as excellent isolation.

A prototype tripler is shown in Fig. 5, which is designed around an antiparallel diode pair that functions as a sinewave to squarewave converter. An inexpensive GaAs flip-chip dual diode[6] with a 3 THz cutoff frequency was used, which lends to the mass producibility of the design. A four-pole stepped-impedance low-pass filter was implemented on the input side, with a 3 dB frequency of 23.6 GHz. The output filter is a four-pole coupled line design with a measured 3 dB bandpass of 38.5–48.3 GHz. The output power at 45 GHz is about 0.5 mW for a 63 mW input, which is the anticipated operating condition for the final array. This power is sufficient to drive the mixer. However, a marginal improvement in the mixer conversion loss could be attained with additional power. Higher output powers could be achieved by combining additional diodes in series with the existing diodes.

The tripler measurements were frequency selective as opposed to a simple power measurement. An Agilent E8257D PSG Analog Signal Generator provided the input signal and the output was measured using an unratioed receiver measurement with an Agilent E8364B PNA Series Network Analyzer. A 2.4 mm coaxial cable was connected between the signal generator and the DUT, while the output was connected directly to the 2.4 mm port of the network analyzer. A source power calibration was applied at the DUT side of the 2.4 mm cable, which was chosen as the input reference plane for these measurements. The output reference plane is at the output 2.4 mm connector. A two-port SOLT calibration was performed on the network analyzer ports as a source/receiver calibration.

The splitting is accomplished with a Wilkinson splitter that was designed with a center frequency of 15.0 GHz. The Wilkinson splitter was chosen because it is compact and is matched at all ports. The 100Ω isolation resistor is a high-frequency flip-chip resistor[7] which has an appropriately small reactance up to 50 GHz.

C) Miniature push-on connectors

The high-frequency circuit boards mate to the modules with miniature push-on connectors[8] which are pictured in Fig. 6. A test board was fabricated with a push-on connector that is mated to a 2.5 cm length of microstrip. A single-stub match was implemented in order to improve the connector performance at the LO frequency of 45 GHz. The test board *S*-parameters are shown in Fig. 6. The return loss from DC-20 GHz is better than 19 dB and at 45 GHz is better than 12 dB. The insertion loss has a maximum of 5.2 dB across the band. These connectors allow for simple connection and disconnection of the MMIC modules, which would enable malfunctioning receivers in a large-format array to be easily swapped, ensuring that there are no dead pixels. The connectors are also compact, which is conducive to designing small MMIC modules. Note that the mechanical support for the MMIC modules is not through the boards, but will be accomplished through a copper mounting structure.

[6] United Monolithic Semiconductors DBES105a.

[7] Vishay thin film microwave resistors.

[8] Corning Gilbert GPPO interconnect series.

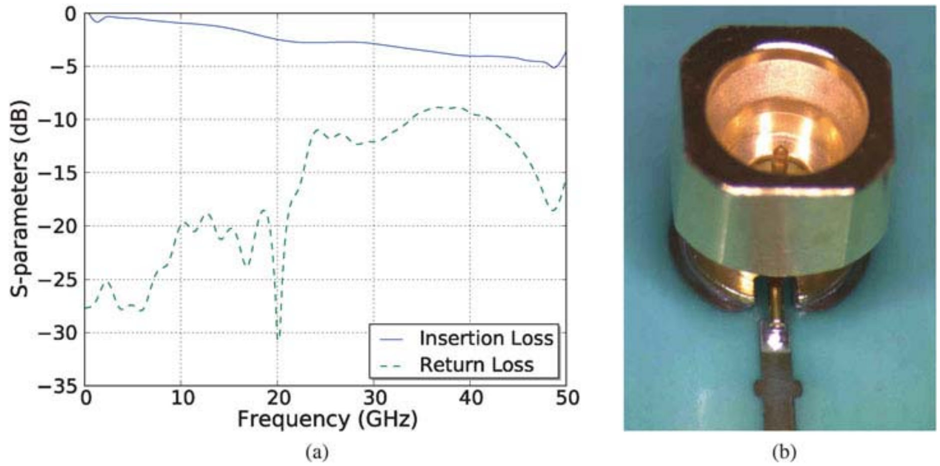

Fig. 6. (a) A plot of the measured performance of a single miniature push-on connector that mates to microstrip. The microstrip section is 2.5 cm, which will be the approximate length of the signal routing boards. (b) A photograph of the connector with a butterfly stub match.

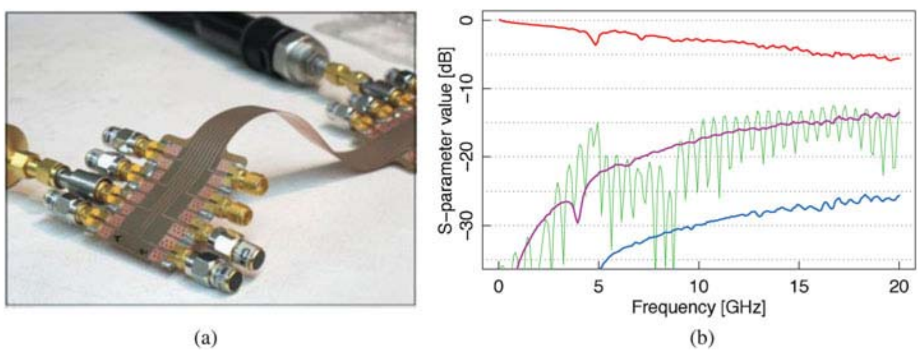

Fig. 7. (a) Photograph of a microstrip test structure with lines using flex circuit technology. The SMA connectors are for testing only. (b) Plot of the measured insertion loss (top line, red), return loss (green), and coupling to closest and next-nearest neighbors (middle, magenta, and bottom, blue curves) of a center line.

D) Routing signals across thermal breaks

The thermal breaks in the IF will be implemented with microstrip transmission lines on flex circuit technology. A proof-of-concept test structure with a set of eight transmission lines has been constructed as shown in Fig. 7. The lines are copper with 17.5 μm thickness and 0.028 mm trace widths and a 25.4 mm ground plane on 0.127 mm polyimide substrate. The corresponding copper cross section is 0.466 mm^2, which would lead to a heat load of 460 mW (290 mW) for a 7.5 cm (15 cm) line over a 20–77 K (77–300 K) temperature gradient. The line spacing for the test structure is 2.54 mm and the total length is 17 cm, which yields better than 15 dB cross talk between adjacent lines across the DC-15 GHz band. Complete *S*-parameter data for the test structure are shown in Fig. 7. The length of each flex line is expected to be no longer than 15 cm, for which the insertion loss would be approximately 2.8 dB. The flex lines will be connected to the board by attaching the ground plane with conductive epoxy and wire bonding the traces. The flex will attach to the cryostat wall via custom clamps, where the lines are then soldered to the connector pins.

V. CONCLUSION

Two W-band heterodyne MMIC receiver modules have been developed for microwave astronomy applications: a SSB prototype module and a DSB module that will be part of a spectroscopic focal plane array. Across the 82–100 GHz band, the prototype SSB MMIC module has exhibited 41 K noise temperature and 29 dB gain when cooled to 15 K. Preliminary testing of the DSB module has shown a 39 K noise temperature and 19 dB gain over the 75–105 GHz band.

Signal routing to and from the MMIC modules is implemented with multilayer high-frequency PCBs and flex circuitry for the thermal breaks. Routing boards with adequate insertion loss and isolation have been demonstrated as well as a prototype frequency multiplier. The routing boards are both economical and scalable to large-format arrays. The integration of a 4-pixel receiver subarray, including DSB MMIC modules and multilayer routing boards, is currently underway.

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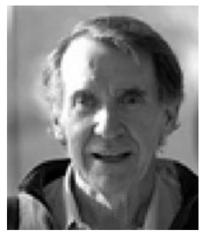

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