ALMA MEMO 429

Fixed-tuned waveguide 0.6 THz SIS Mixer with Wide band IF

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ABSTRACT

The Atacama Large Millimeter Array (ALMA) requires low noise SIS receivers for frequencies from about 80 GHz to 950 GHz with a very large IF bandwidth (8 GHz SSB upper or lower sideband, 8 GHz DSB or 4 GHz dual sideband, upper and lower sideband). Since there will be a large number of antennas in the array (currently 64), additional requirements such as high reliability, low cost, and the production of a relatively large number of mixers have to be addressed.
In this paper we report the results of a waveguide mixer with a fixed backshort for ALMA band 9 (602 – 720 GHz). The mixer is based on standard Nb/AlO_x/Nb SIS junction technology. This mixer was tested with a wide band IF amplifier with and without an isolator. Mixer measurement results for different LO frequencies across a wide IF band (4-12) GHz) will be presented. DSB Receiver noise across the both RF and IF band was measured, and receiver noise as low as 136 K at 650 GHz was demonstrated over the wideband IF. Finally, the possibility of a small production series of such a mixer is discussed with results on a first batch of mixer-blocks will be presented.

INTRODUCTION

The Atacama Large Millimeter Array (ALMA) requires low-noise SIS receivers for frequencies from about 80 GHz to 950 GHz with very large IF bandwidth (4-12 GHz). ALMA will be built in the Atacama Desert (Chili) at the altitude of more than 5 km. The atmospheric conditions for mm-wave astronomical observations at this site are among the best in the world. The array will consist of at least 64 antennas, each with a diameter of 12 m.
The Alma frequency band is divided into ten subbands. These bands coincide with regions where the atmosphere is relatively transparent and astronomical observations are possible. The receivers for the different subbands will be mounted in a common cryostat supporting three temperature levels: 4.3 K, ~10 K and 80 K. Each subband receiver is contained in an independent "cartridge" that can be mounted in the receiver cryostat without disturbing other subbands. This cartridge contains a complete receiver system including SIS mixers, LO subsystem, IF amplifiers and all necessary optical components.

The remoteness of the site and the large number of receivers impose additional requirements on the receiver design such as absence of moving parts, an as simple as possible layout, low cost, and the possibility of series production.
In this paper we report mixer designs based on standard $Nb/AlO_x/Nb$ SIS junction technology in a waveguide mixer block for ALMA band 9 (602 – 720 GHz). The mixer does not contain moving parts e.g., a backshort. We present results on the extension of the IF bandwidth from 1.1-1.7 GHz to 4-8 GHz and 4-12 GHz by using an NRAO wide-band IF amplifier and PamTech 4-8 GHz and 4-12 GHz isolators. We will also present our approach to small series production of such a mixer.

MECHANICAL DESIGN OF THE MIXER

Fig. 1 shows the design of an ALMA band 9 single-ended double sideband (DSB) waveguide mixer. Similar designs have already been implemented in other mixers [1]. The design goal was best possible performance combined with simplicity and series fabrication possibility. The mixer consists of several parts:

- a horn (1),
- a centering ring (2) aligning the horn with the backpiece,
- a mixer backpiece (3) which holds the SIS tunnel junction and the IF connector,
- a threaded cap to hold horn and backpiece together (4),
- a magnet consisting of a coil (not shown) and two pole shoes (5),
- a mounting structure (not shown).

The parts of the mixer which are most critical to the performance are the horn, the backpiece and the substrate with the junction and the tuning structures. The diagonal horn is used for experimental mixers, but the design easily allows it to be replaced with an appropriate corrugated feedhorn. The main idea in the design is to machine all critical surfaces to such an accuracy that mutual alignment between the different parts of the mixer occurs automatically upon assembly. This design also achieves a good coupling of the magnetic field flux from the coil to the junction, which is critical for Josephson noise suppression at these frequencies. The distance between pole pieces is only 1 mm with the junction at the center. The DC/IF connection is made by means of a standard miniature SMP-type connector. This is one of the smallest connectors available, allowing us to decrease the transmission line length between the junction and any other IF components, facilitating amplifier-mixer integration. The mechanical design does not incorporate an external bias-tee. However, in certain configurations, a standard Radiall bias-tee was used.

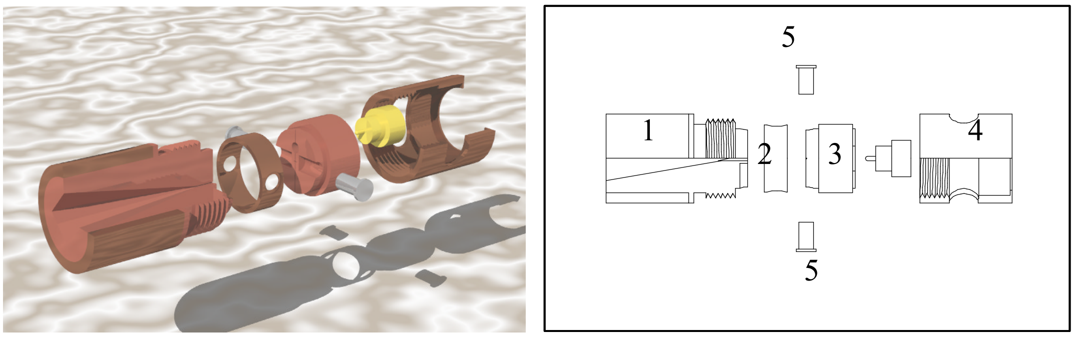

Figure 1: Mechanical design of the mixer.

For the magnet we use a coil of about 6000 turns of 63.5 micron diameter Cu-cladded Nb wire. For the core of the magnet and the pole pieces we use VacoFlux 50, which has a maximum permeability of 9000 and a saturation polarization of 2.35 T.
The waveguide has a cross-section of 100 x 400 μm. The cross-section of the substrate channel in the backpiece is 70 x 100 μm and the backshort cavity is about 200 μm deep. The backshort cavity is produced by stamping it in the copper block.
The substrate is 2.1 mm long, 50 μm thick and 70 μm wide and it contains a Nb-based SIS tunnel junction. It is glued in the channel and contacted with silver paint.

MIXER CHIP LAYOUT

A photograph of a mixer chip glued into the substrate channel is shown in fig. 2. The substrate material is fused quartz. Standard Nb technology was used for making the thin film layer structure. Optical lithography was used in all definition steps including the patterning of the 1 μm^2 SIS junction. The RF design of the coupling between the waveguide TEM mode and the SIS junction is similar to the one used earlier, for instance in [2] and [3]. The energy is coupled to a bow-tie waveguide probe and transferred via a Chebyshev type two-stage impedance transformer to the junction-tuner combination. This transformer is formed by two microstriplines connected in series. The bottom electrode of this microstripline is formed by the bottom part of the bow-tie probe. The junction is located at the end of the tuner section of the microstripline. A choke structure is used to prevent RF signals from leaking into the IF/DC bias leads. A low impedance $\lambda/4$ line is used to provide a virtual short circuit between the waveguide probe and the waveguide wall at RF.
The junction's R_nA value is about 35 $\Omega\mu m^2$ and its normal resistance R_n about 34 Ω. The thickness of the Nb is about 200 nm for the bottom layer and about 600 nm for the top layer. The thickness of the SiO_2 insulator is about 250 nm.

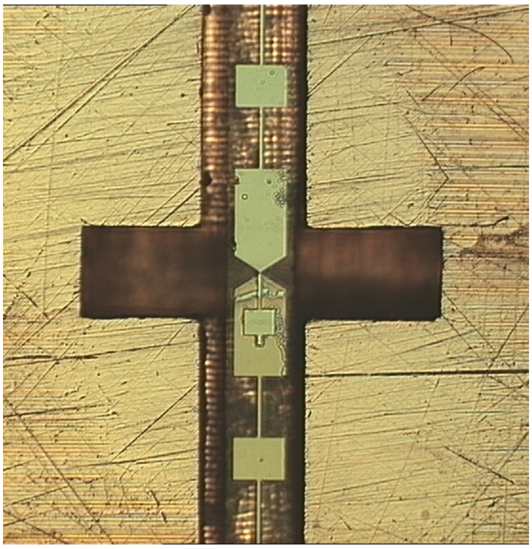

Figure 2: Photograph of a mixer chip glued into a back piece, looking straight into the backshort cavity.

WIDE-BAND IF AMPLIFIER AND ISOLATORS

For each mixer/IF amplifier configuration, a wide band 4-12 GHz IF amplifier provided by the NRAO Central Development Laboratory (CDL) was used. This amplifier is identical to the design used in experiments done at the CDL, where a single-ended SIS mixer was directly connected to its IF amplifier [4]. The gain of the amplifier is about +34 dB, with an equivalent noise temperature (at a physical temperature of 12 K) of 4-7 K across the IF band. The total DC power dissipation is almost 8mW. Low power dissipation is important to prevent heating of the mixer junction, and to reduce the heat load on the 4 K stage. A mixer bias-tee is incorporated into the amplifier, which facilitates connecting the amplifier to the mixer, and thus eliminates the need for an external bias-T. The amplifier is unconditionally stable, which is necessary since the input source impedance of the amplifier from the mixer can vary greatly from a low impedance to a high (and even negative) impedance, depending on the LO frequency. The input return loss of the amplifier is better than 10 dB from 5 to 10.5 GHz. This is important to assure a nominal value for the mixer gain and input RF return loss to the mixer.

Two cryogenically coolable isolators were used for experiments: a commercially available 4-8 GHz isolator from Passive Microwave Technologies (PamTech) [5] and a new 4-12 GHz prototype isolator under development by PamTech(1). The photograph of both isolators is presented in fig. 3. Despite its larger size, the 4-12 GHz isolator may have sufficient performance to be used in ALMA receiver cartridges because it allows mixer and amplifier to be separated, and provides a clear 50 Ω interface between them. The mass of 4-12 GHz isolator is about 120 grams. Preliminary cryogenic measurements of this isolator at a temperature of 4 K have shown its insertion loss to be below 1 dB from 5-13 GHz.

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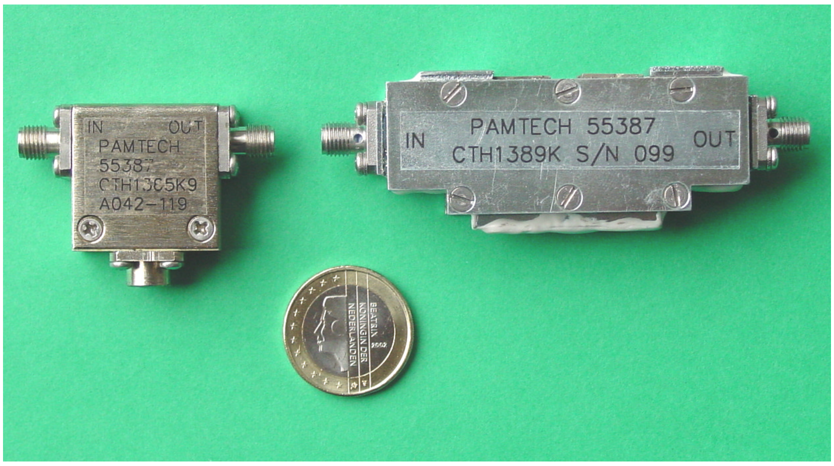

Figure 3: Photograph of a commercially available 4-8 GHz PamTech isolator (left) and the 4-12 GHz development prototype (right).

EXPERIMENTAL SETUP

We used a standard Y-factor measurement technique to determine receiver noise temperature. The mixer was mounted inside the vacuum space of a liquid helium cryostat at 4.2 K. A high-density polyethylene lens was used to refocus the wide angle beam from the diagonal horn onto an external hot/cold load. The Mylar film of 125 μm thickness was used as vacuum window. A GoreTex sheet (expanded Teflon) of 3 mm thickness at liquid nitrogen temperature was used as an infrared radiation filter. A Mylar sheet of 12-15 μm thickness was used for local oscillator (LO) injection. A Gunn oscillator followed by a diode doubler and a diode tripler was used as an LO. Black body absorbers at 300K and 77 K were used for receiver calibration. All presented noise temperatures are uncorrected for beamsplitter loss, and a Callen/Welton formula [6] was used to obtain black body radiation temperatures.
Several mixer-amplifier configurations are shown in fig. 4. A comparison between these options was made, keeping other components of the receiver the same.

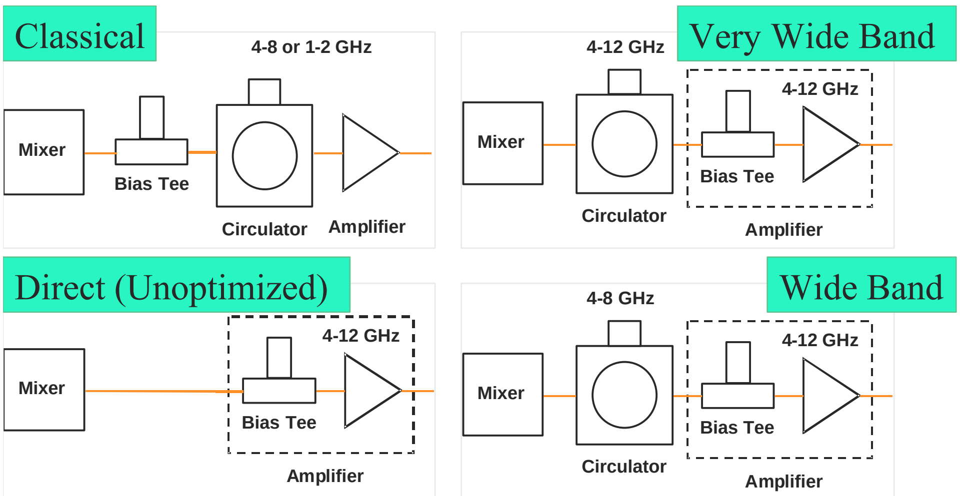

Figure 4: Measurement schemes.

The “classical” configuration to test the mixer was with a conventional L-band amplifier (1.1-1.7 GHz) and external bias-tee between mixer and circulator.
In the “wide band” and “very wide band” options, an isolator was used between mixer and amplifier. It was possible to use the bias-tee integrated in the amplifier because both isolators allowed the biasing of the SIS mixer through them.

Since the IF amplifier was designed to be unconditionally stable, a “direct” option was also tried as an intermediate step to direct integration of the SIS mixer and IF amplifier. In directly connecting the mixer to the amplifier, it is important to point out that no optimisation was done between the mixer and amplifier. An (approximate) 2 cm length of semi-rigid coax cable was connected between the mixer and IF amplifier. This experiment was done to “just see what happens”, and by no means should not be taken as a final comparison between direct integration and using an isolator between the mixer and amplifier.

MEASUREMENT RESULTS AND DISCUSSION

Typical I-V and output IF power bias dependencies for the mixer are shown in fig. 5 (left). The measurements were done by using a 6-8 GHz band-pass filter in the warm IF amplifier chain, consisting of two room temperature IF amplifiers of 30 dB gain each. The curves in fig. 5 show that the Josephson noise can be suppressed and that no artifacts are introduced by the large IF bandwidth. The receiver noise temperature measured for different IF amplifier connection options is presented in fig. 5 (right). One can see that all configurations are comparable in equivalent noise temperature. The increase in noise temperature for options with high IF frequency as compared to the L-band case is due to the fact that at these LO frequencies the upper sideband already hits the upper edge of the receiver band. The IF output power and noise temperature vs. IF frequency for different options is shown in figs. 6 to 8. The power curves were all taken at the same optimum bias point while changing the receiver input from 300 K to 77 K. The IF output power ripple for the “wide band” option (fig. 6) is less than 2 dB per 2 GHz, which is within the ALMA specification. The noise temperature variation across the IF band is also sufficiently small.
Similar receiver quality can be seen in the “very wide band” case (fig. 7). The dip in output power at around 7 GHz can probably be attributed to one of the SMA connectors used in the 4-12 GHz circulator. The decline in the noise temperature at the higher end of the band (frequency more than 11 GHz) is due to parasitic capacitance of the mixer tuning structures and parasitic inductance due to long choke-structures used in this particular mixer design.

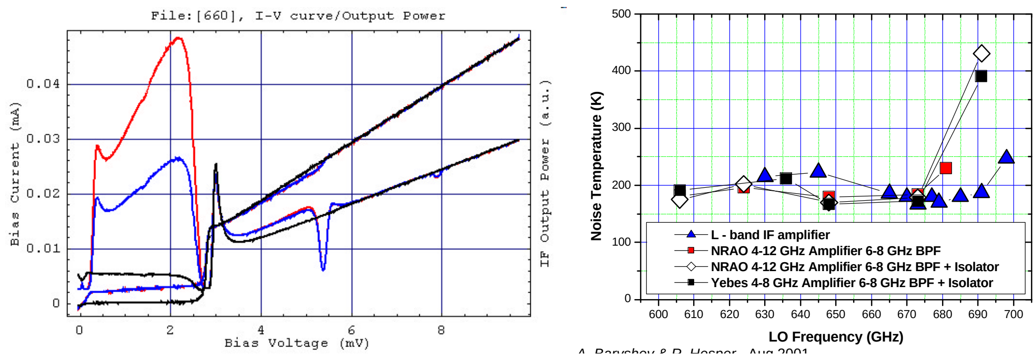

Figure 5: Typical I-V curves and IF output power (left) and summary of receiver noise temperatures for different mixer-amplifier coupling options (right).

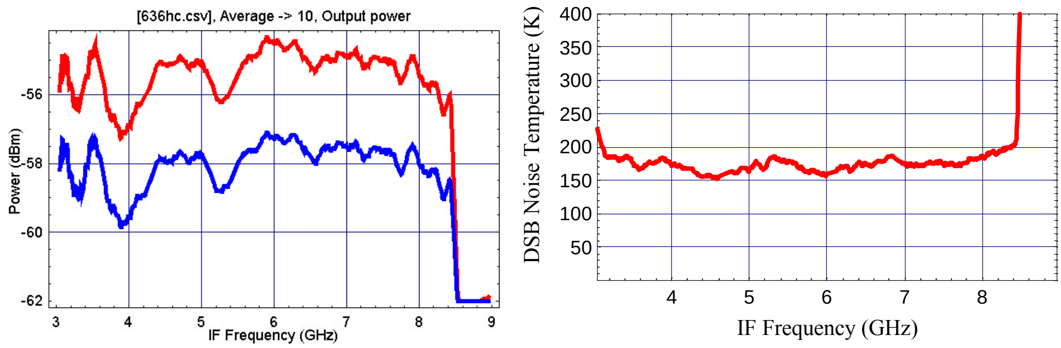

Figure 6: Receiver response with the 4-8 GHz system with isolator ("Wide band" option).

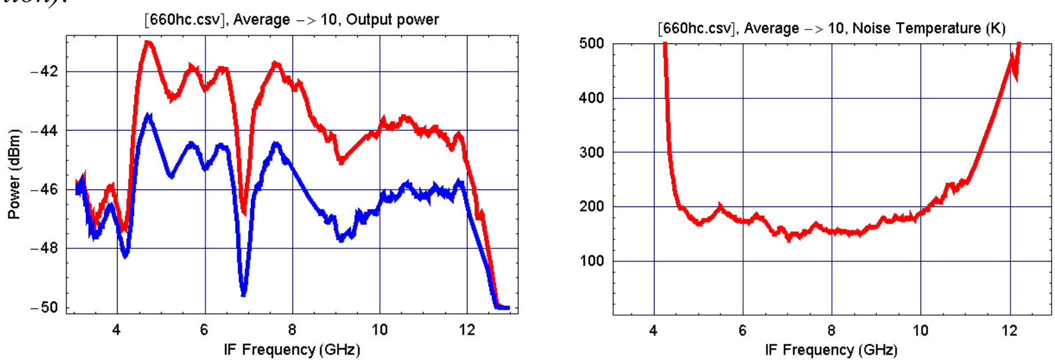

Figure 7: Receiver response with the 4-12 GHz isolator ("Very Wide band" option)

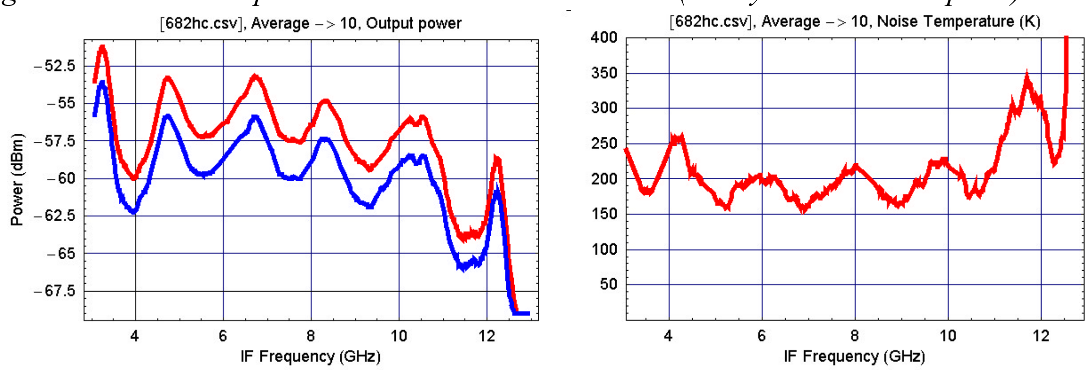

Figure 8: Receiver response without isolator ("direct" connection via 2 cm semi-rigid cable)

We expect that mixer performance can be improved at higher IF frequencies by minor design modifications. The lower boundary of the IF band is shifted upwards because of the shift in the 4-12 GHz circulator operation band.

The results for the "direct connection" case are shown in fig 8. As expected, the IF output power had a considerable amount of ripple (in this measurement, about 8 dB ptp.) A noise temperature ripple of the order of 25% is also visible. No parasitic oscillations were observed in the IF amplifier during the measurements. As mentioned earlier, the interface between the mixer and amplifier was not optimised, and as a result, *a direct comparison between the other configurations should not be made*. This test was done to see what would happen when the IF amplifier was directly connected to the mixer, and what was seen is what was expected. This configuration requires further optimisation of the mixer and amplifier designs to reduce the amplitude of these ripples. SRON and NRAO are collaborating on an optimised direct mixer/amplifier design. So far, a potentially successful design has been realised through simulation. Further details have to be worked out such as the design of the RF choke structure of the mixer to enhance the performance at the upper end of the IF band, and the mechanical interface between the mixer and amplifier.

SMALL SERIES PRODUCTION

One of the goals of the current mixer design is the feasibility of series production. To investigate this a collaboration was set up with a company specialized in fine-mechanical machining, Witec B.V. (Ter Apel, Holland), to fabricate the mixer backpiece (the most difficult part) on their CNC milling machines with as little human intervention as possible. Several test runs were conducted, transferring the SRON expertise of manual production to the computer-controlled method in an iterative way. Because self-alignment of the different parts of the mixer structure is a central requirement of the design, special attention was paid to the accurate positioning of the backshort cavity with respect to the reference circle, as well as to the depth of the stamped cavity, which plays a large role in tuning the receiver.
After a few iterations, during which the tooling was perfected, critical alignments had converged to within about 10 μm, which should be enough to provide good mixer performance, while the machining time had dropped to less than one hour per backpiece. The latter should be contrasted to the time it took a skilled technician to produce a backpiece by manual means, which was of the order of a week.
One of the CNC-produced backpieces was tested together with a diagonal horn, and its performance turned out to be very comparable to the classical hand-made backpieces.

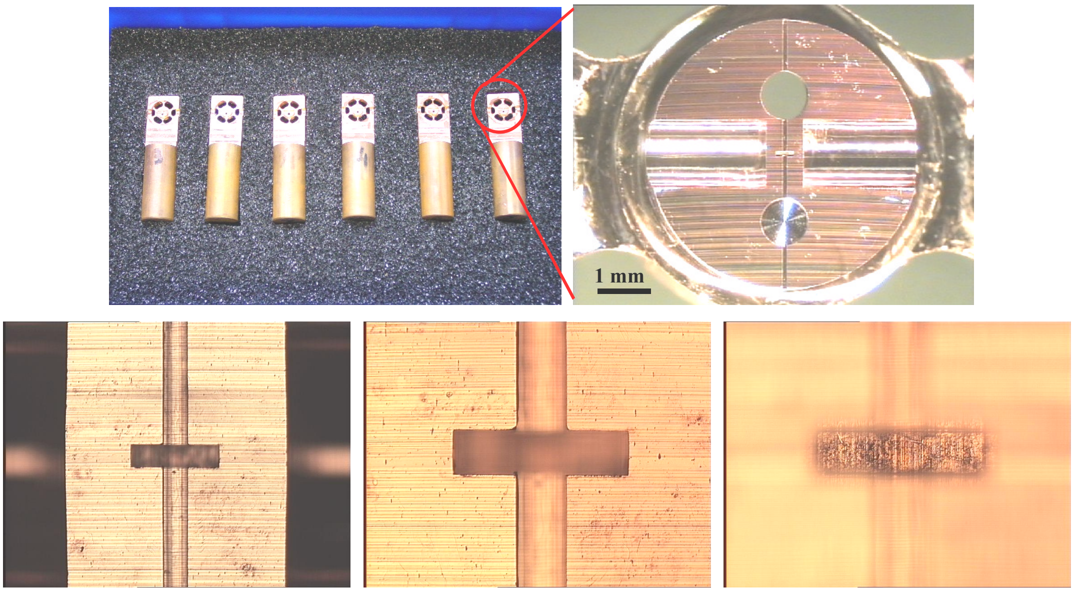

Figure 9: The small series of backpieces and photographs demonstrating the cavity quality. The middle and the right photographs at the bottom series are focused on the top and bottom of the cavity, respectively.

CONCLUSION

A compact and efficient waveguide mixer design for ALMA band 9 was demonstrated. Four different IF amplifier connection schemes were evaluated experimentally. Wide band (4.5-11 GHz) IF operation was achieved with the development model of a 4-12 GHz isolator, yielding sufficient performance to be used in low noise receiver systems. However, this first prototype isolator doesn't yet cover the full 8 GHz of instantaneous IF bandwidth required by the ALMA specification. Series production of this mixer design with sufficiently tight tolerances has been demonstrated.

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