An ultra-broadband optical system for ALMA Band 2+3

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An ultra-broadband optical system for ALMA Band 2+3

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ABSTRACT

ALMA is the largest radio astronomical facility in the world providing high sensitivity between 35 and 950 GHz, divided in 10 bands with fractional bandwidths between 19 and 36%. Having a lifespan of at least 30 years, ALMA carries out a permanent upgrading plan which, for the receivers, is focused on achieving better sensitivity and larger bandwidths. As result, an international consortium works on demonstrating a prototype receiver covering currents Bands 2 and 3 (67 to 116 GHz) which corresponds to a fractional bandwidth of 54%. Here we present the preliminary design, implementation and characterization of suitable refractive optics. Results indicate an excellent performance in good agreement with simulations.

Keywords: Ultra-broad bandwidth, heterodyne detection, ALMA, optics, profile-optimized corrugated horn, Band 2+3.

1. INTRODUCTION

The Atacama Large Millimeter Array (ALMA) is the largest millimeter and submillimeter radio telescope in the world. It combines an array of 66 classical Cassegrain antennas providing high sensitivity between 35 and 950 GHz. This frequency range is divided in 10 bands with fractional bandwidths between 19 and 36%. Having a lifespan of at least 30 years, ALMA is carrying out a permanent upgrading program for every one of its subsystems. Regarding its receivers the program focuses on achieving better sensitivity and larger bandwidths at the RF and IF level. Due to the lack of good wideband and very-low-noise amplifiers above 80 GHz, astronomical receivers, including those of ALMA, use superconductor-insulator-superconductor (SIS) mixers as the first element in the receiving chain. However, nowadays, low-noise amplifiers based on high-electron-mobility transistors (HEMTs), combined with Schottky diodes, have the potential to achieve similar noise levels of traditional SIS mixers at the 3-mm band. Moreover, HEMT amplifiers are inherently easier to use and more stable than SIS mixers, promising, thus, a new generation of receivers. For these reasons an international consortium has been formed to demonstrate this technology in a prototype receiver covering current Bands 2 and 3 of ALMA (67 to 116 GHz) corresponding to a fractional bandwidth of 54%. Such receiver may allow to perform new astronomical measurements not achievable by receivers covering the two bands independently. Moreover, it could vacate space inside the cryostat for new instrumentation. Here we present the preliminary design, implementation and characterization of two optical systems that cover the full range of ALMA Band 2+3.

2. GENERAL CONCEPT

Since the optics is the first subsystem of any receiver, low noise figure and maximum aperture efficiency are fundamental for best sensitivity. However, a conjunction of several factors as the large bandwidth, truncation set by existing cryostat apertures, dielectric couplings, losses in the materials, construction constraints and cost limitations, makes extremely challenging achieving these goals. To overcome these problems, several options have been studied including reflective and refractive optics. So far, the most promising, complying with all constraints, is the latter. As it can be seen schematically in figure 1, it consists of a corrugated horn, a modified Fresnel lens and an ortho-mode transducer (OMT). Two different optical systems have been constructed and characterized. These systems are similar to previous work done in the context of ALMA Band 1 (35-52 GHz) [1].

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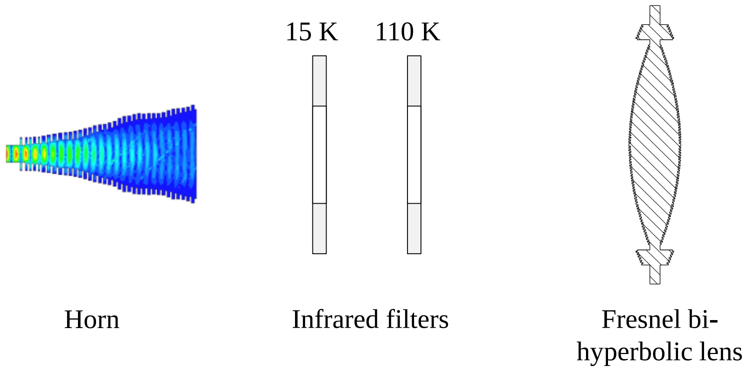


Figure 1. Basic layout of the optical system for Band 2+3 (not to scale). Infrared filters are already installed in all ALMA cryostats and have been taken as restrictions in the optimization process.

3. COMPONENTS

3.1 Horns

Two corrugated horns, implemented using different methods of construction, were studied (figure 2). One is a horn whose profile was optimized for best performance [1]. Although the profile allows construction in a CNC lathe from a single block, initially we have implemented it in a split block following a concept described earlier for band Q [2]. The other horn is a sin-squared profiled corrugated horn fabricated by stacked metallic rings carefully assembled together.

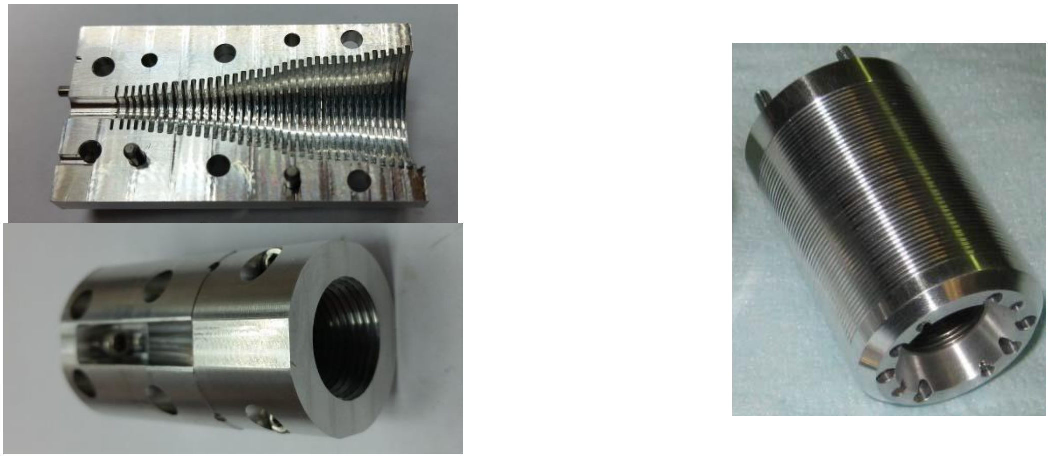
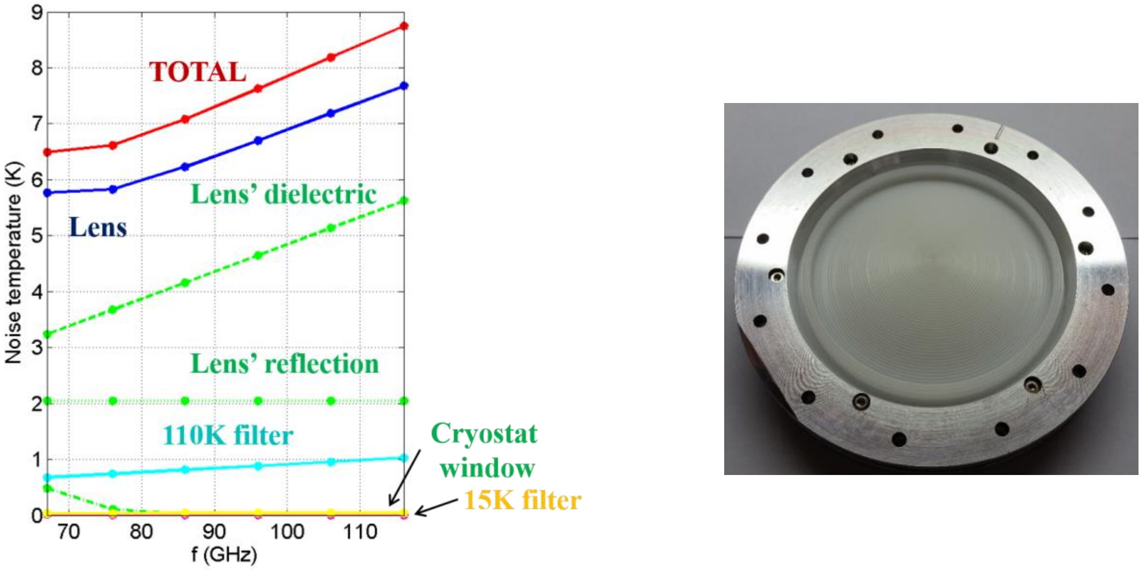

(a) (b)

Figure 2. (a) Profile-optimized horn constructed as split block at UChile. (b) Sin-squared corrugated horn implemented by stacked metallic rings at INAF.

3.2 Lenses

To minimize the noise contribution of the optical system a one-step zoned lens was selected for each horn [1]. The parameters of each lens were carefully optimized at NAOJ to maximize the frequency coverage and aperture efficiency, and to reduce losses. Simulations indicate that the lenses add in average less than 7 K to the receiver noise temperature. Moreover, we estimate that the systems implemented with the elements presented here have aperture efficiencies better than 82%. Noise contribution of one of the lenses and its implementation are presented in figure 3.

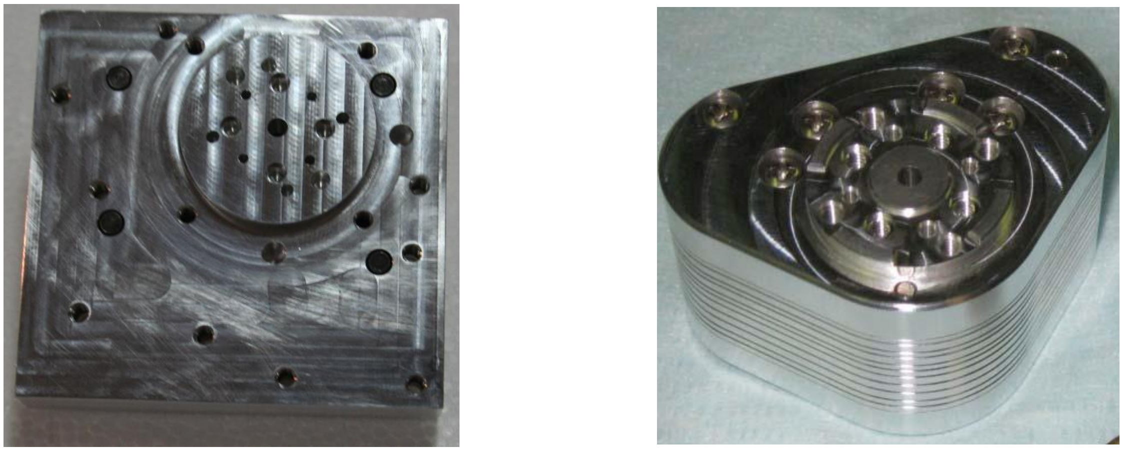


(a) (b)

Figure 3. (a) Noise contribution of one of the studied lenses. (b) Implementation from an HDPE block.

3.3 Orthomode transducers

As OMT we have studied two designs based on a turnstile junction. Compromises have been made in the length of the waveguides to minimize losses and avoid trap modes. The fabricated OMTs are presented in figure 4.



(a) (b)

Figure 4. (a) OMT implemented in four plates at UChile. (b) OMT implemented in nine plates at INAF.

4. EXPERIMENTAL SETUP

A near-field beam-pattern measuring system was set up at ESO facilities. The near-field data obtained in this way is later transformed into far-field data using an algorithm based on Fourier Transform. A diagram and a photo of the system are presented in figure 5. We have used this experimental setup to characterize the two optical systems formed with the components presented in section 3.

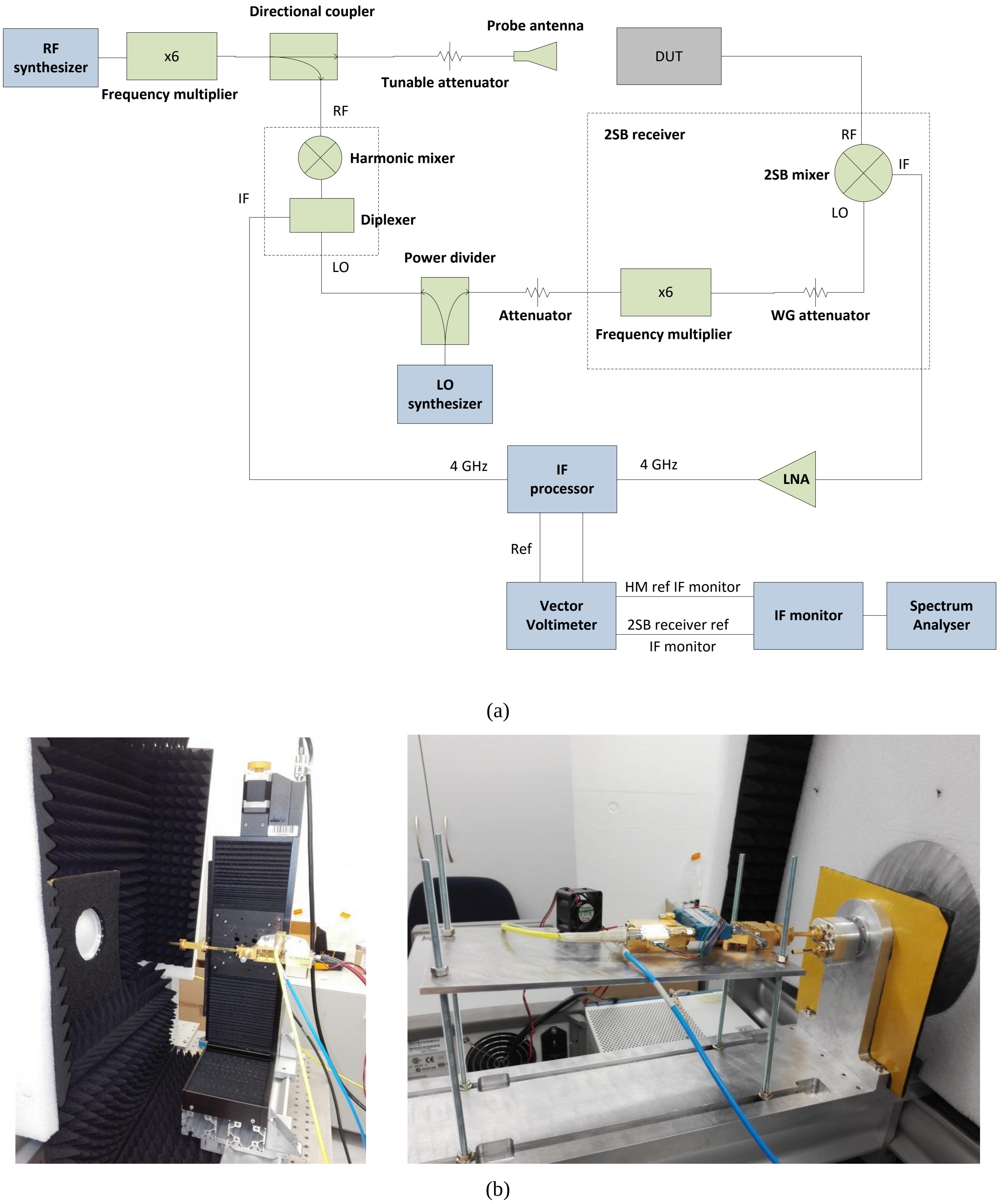
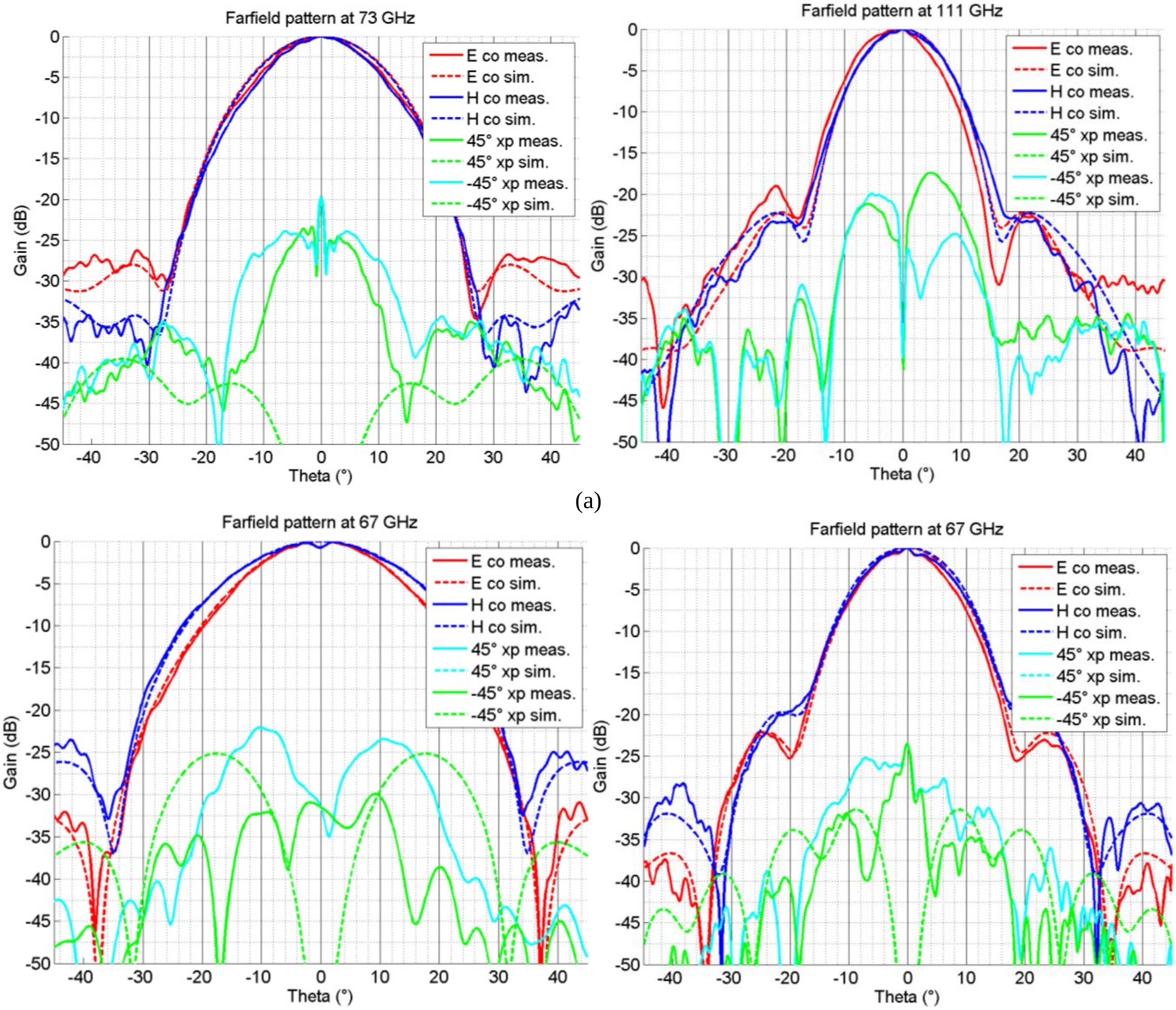


Figure 5. Near-field beam-pattern measurement system. (a) Schematics. (b) Front and back views.

5. RESULTS & DISCUSSION

Two different optical systems were characterized. The first system was mounted using the components developed at Universidad de Chile while the other used components developed at INAF. The lenses for both sets of components were designed at NAOJ and fabricated by Universidad de Chile. The beam patterns at two different frequencies are shown in figure 6. Co-polarization patterns show good agreement between simulation and measurement. However, cross-polarization patterns are larger than expected. We attribute this to small fabrication errors that are being addressed for future implementations.



(a)

(b)

Figure 6. Far-field beam patters of the two different systems at two different frequencies. (a) System developed at Universidad de Chile. (b) System developed at INAF.

From the beam patterns of both optical systems, we have calculated the aperture and polarization efficiencies. They are presented in figure 7 together with those obtained from simulations. Except for polarization efficiency, efficiencies are well into specifications for most of the frequency points. Non-compliance in polarization efficiency may be attributed to fabrication errors of the horn and small misalignments. All these problems are being addressed currently. At the moment of writing, new components have been fabricated and a second measurement campaign is being conducted at ESO. Finally, it is necessary to mention that other optical systems were mounted combining different components. Results are not presented here for the sake of simplicity. The different combinations also hint to problems of fabrication and alignment.

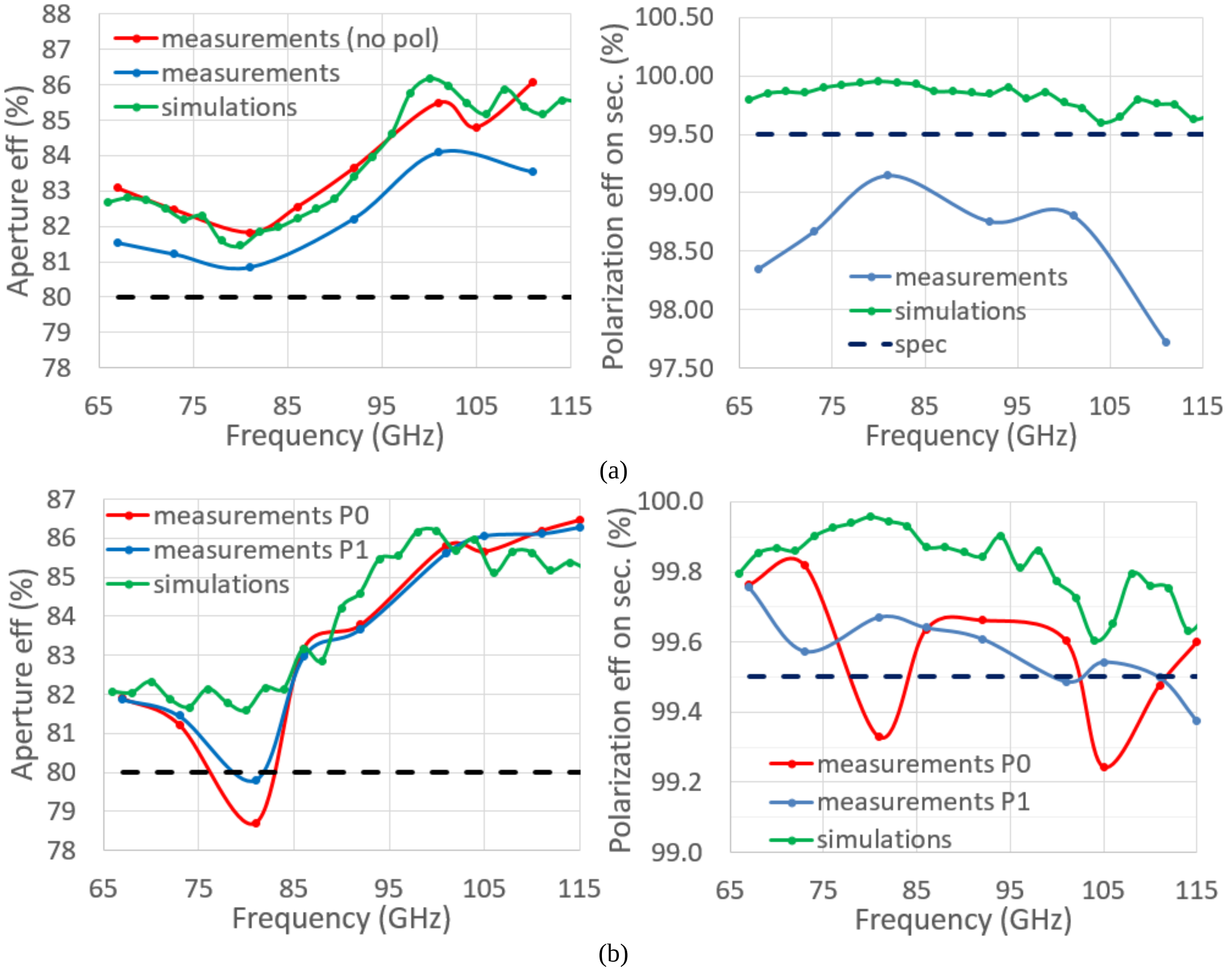


Figure 7. Measured and simulated aperture and polarization efficiencies. Thick dashed line in every graph indicates ALMA requirements. (a) System developed at Universidad de Chile. (b) System developed at INAF.

6. CONCLUSIONS & FUTURE WORK

Here we have presented the first iteration towards obtaining an optical system that covers the frequency range corresponding to Bands 2 and 3 of ALMA. The preliminary implementations show excellent performance although more optimization is needed. A second campaign of measurements is being conducted at the moment of writing with new versions of horns and OMTs. Moreover, we have started a study to investigate new materials for the lens. A recent study [3] demonstrates that high-purity silicon has an extremely low loss tangent allowing to diminish the noise temperature contribution of the lens.

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