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The ALMA Band 6 (211-275 GHz) Sideband-Separating SIS Mixer-Preamplifier

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ABSTRACT

The ALMA Band 6 (211-275 GHz) receivers use sideband-separating SIS mixer-preamplifiers with dual 4-12 GHz IF outputs. The sideband-separating mixers are of the phasing type, with the LO driving two component mixers in-phase and the RF signal connected to the mixers through a quadrature hybrid. The IF outputs of the mixers are amplified, then combined in a quadrature hybrid which separates the upper and lower sideband signals. The RF circuit components are all in a single split waveguide block — quadrature hybrid, LO power divider, LO couplers, cold image termination, and the two mixer chips. To achieve the wide IF bandwidth, a low-parasitic mixer is used and the preamps are bolted directly to the mixer block.

INTRODUCTION

The Atacama Large Millimeter Array* will have 64 antennas and will cover 35-960 GHz in ten bands using dual-polarized heterodyne receivers. In Band 6 (211-275 GHz), sideband-separating SIS mixers with dual 4-12 GHz IF outputs are used. Sideband separation (or rejection) in the front end is desirable for spectral line observations to reduce the contribution of atmospheric noise in the image sideband to the overall system noise. There are three ways to suppress the image response of a broadband mixer receiver: (i) A filter can be inserted in front of the mixer to terminate the mixer reactively at the image frequency. This is difficult in widely tunable receivers. (ii) A tunable four-port diplexer with a cold image termination can be used. This can be done quasioptically, *e.g.*, using a Martin-Puplett interferometer, but has limited IF fractional bandwith, requires mechanical tuning, and is cumbersome at millimeter wavelengths. (iii) A sideband-separating mixer can be used, and this is the approach used in the present work. Different approaches to sideband separation are described in [1]. At the 1998 ISSTT, we described a single-chip Band 6 sideband-separating mixer [2], and in 2000 proposed a waveguide version of a similar circuit but with balanced mixers [3]. Other waveguide based sideband-separating SIS mixers have been described by Claude *et al.* [4], Belitsky *et al.* [5], and Chin *et al.* [6]. The configuration used in the present work is shown schematically in Fig. 1. Of particular importance in Fig. 1 is the resistor R_{IM} on the fourth port of the RF quadrature hybrid. From the symmetry of the circuit, it is clear that this resistor is the image source for the sideband-separating mixer; USB thermal noise from this resistor is downconverted to the LSB IF output port, while LSB thermal noise appears at the USB IF output.

MIXER CIRCUIT DESIGN

Although a single-chip design with all the RF components on the same substrate may seem attractive, the large size of the chip compared with that of a simple elemental mixer results in a relatively small number of mixers per wafer. As ALMA requires well over 100 mixers for each band, we explored the feasibility of machining the RF components as waveguide circuits in a single E-plane split metal block which also contains two elemental mixer chips. The most difficult component to fabricate with acceptable gain and phase imbalance is the waveguide quadrature hybrid, but this

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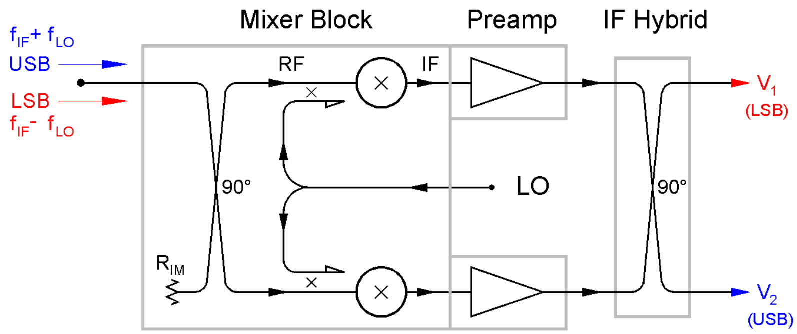

Fig. 1. Sideband-separating mixer configuration used for Band 6.

is possible using a branch-line coupler machined with a small (0.004" diameter) end-mill[1] with long (0.020") working depth. The quadrature hybrid is similar to those described in [7]. The LO power splitter is a matched E-plane T-junction [8]. Cross-guide and broad-wall hole-coupled waveguide directional couplers, commonly used for LO injection, are not suitable for E-plane split block circuits. Instead, the LO couplers use multiple broad-wall coupling probes [9] [10]; the coupling can be changed from 22 dB to 18 dB by using six probes instead of four. The waveguide loads on the LO couplers and the RF hybrid must be compact but well matched at the 4 K operating temperature; their design is described in [11]. Geometrical constraints imposed by the preamplifiers and the magnetic circuit make it desirable for the signal and LO input waveguides to enter the mixer perpendicular to the plane of the split between the halves of the block. This requires a well matched H-plane bend, as described in [8]. Bias to the elemental mixers is provided through the IF preamplifiers as in [12], which eliminates the need for a separate bias connector on the mixer block and also allows the preamps to be mounted closer to the mixer chips. Figure 2 shows one half of the mixer block. Figure 3 shows a front view of the assembled mixer-preamp with the lids removed, and Fig. 4 shows a rear view of the assembly. The magnetic pole pieces, visible in Fig. 3, are made of annealed Consumet magnet iron after the design described in [13] and [14].

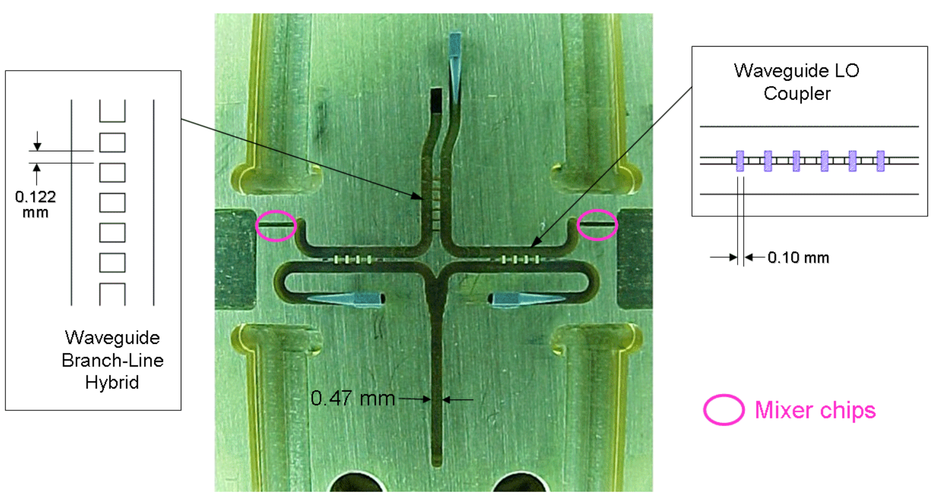

Fig. 2. One half of the mixer block. At the top are the cold image termination [11] and the signal input waveguide which enters from below the page via an H-plane bend [8]. The signal is split by the branch-line hybrid and passes to the mixer chips via the LO couplers [9]. The LO power enters the lower waveguide from above the page via an H-plane bend, is divided by the matched T-junction [8] and is coupled to the mixers through the LO couplers.

[1] Cutting Edge Technologies/Richards Micro-Tool, Inc., 250 Nicks Road, Plymouth, MA 02360.

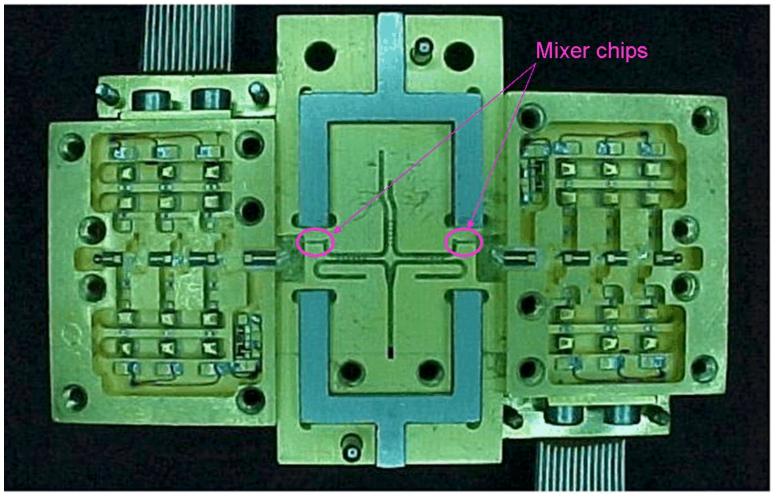

Fig. 3. Mixer-preamp assembly with the mixer and preamp lids removed. The Y-shaped magnetic pole pieces are visible in the upper and lower parts of the mixer block. The IF/DC connection between the mixer chips and the preamplifiers is by a (series) bond wire and (shunt) chip capacitor.

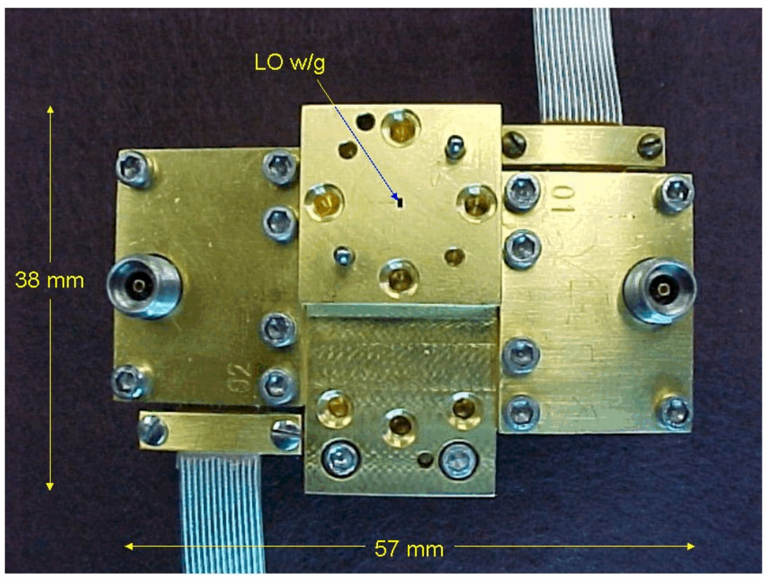

Fig. 4. Mixer-preamp assembly showing the LO input waveguide and the type-K IF connectors.

SIS MIXER DESIGN

The elemental SIS mixers, shown in Fig. 5, are based on our earlier broadband wide-IF design [15]. The main differences are the use of a quasi-lumped element tuning circuit in place of the quarter-wave short-circuit stubs in [15] and a shorter RF choke to reduce parasitic capacitance and inductance in the IF circuit. The mixers are fabricated on fused quartz substrates using the UVA Nb/Al-AlO_x/Nb process [16], [17]. The upper frame of Fig. 5 shows the whole mixer chip with the waveguide coupling probe on the left and a length of suspended stripline leading to a broadband transition to capacitively-loaded coplanar waveguide (CLCPW) [1]. The Nb ground plane has gold contact pads (top and bottom in the upper frame) which contact shoulders in the mixer block. The middle frame in Fig. 5 shows the end of the CLCPW (at the left) connected to a short microstrip line and a short section of CPW. The microstrip and CPW form a shunt-C/series-L impedance transformer. Between the CPW and the series array of four SIS junctions, a pair of resonators (at the top and bottom of the middle frame) are connected in parallel via short microstrip lines. The resonators each consist of a short short-circuit microstrip stub in parallel with a short open-circuit microstrip stub and closely approximate a parallel LC circuit. The short microstrip lines between the resonators and the main signal path have negligible effect on the circuit. Details of the four-junction array are shown in the lower frame. To the right of the junctions is a section of microstrip, forming a capacitor to ground, followed on the right by a high impedance RF choke circuit consisting of a quarter-wave high impedance CPW and a microstrip capacitor. At the right end of the substrate is the IF/DC bonding pad. The circuit minimizes parasitic inductance and capacitance in the IF circuit in two ways [15]: (i) IF currents are kept out of most of the RF circuit by the low impedance paths through the ground vias at the ends of the inductors in the RF resonators, and (ii) the short, high impedance RF choke has low capacitance as seen at IF.

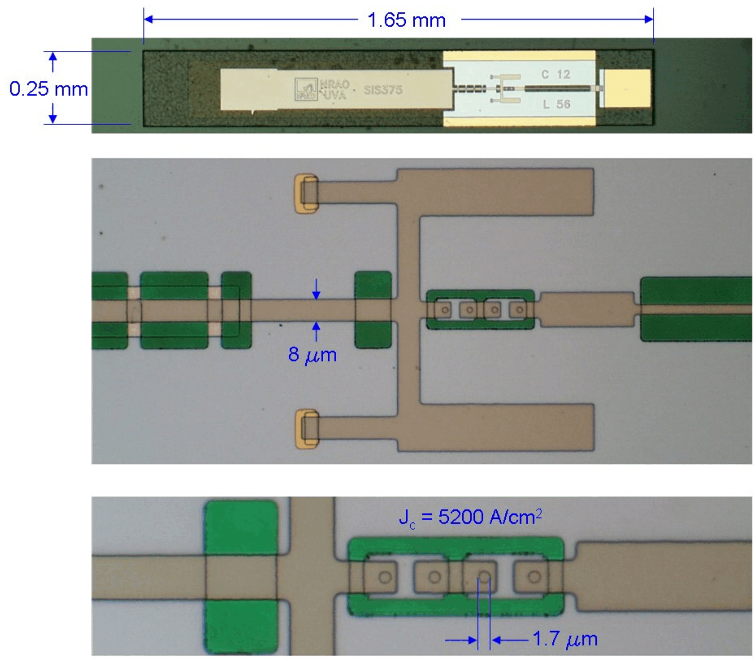

Fig. 5. The SIS mixer substrate.

MIXER-PREAMP MEASUREMENTS

There are two ways to define the image rejection (or sideband ratio) of a sideband-separating receiver. These are illustrated in Fig. 6. In spectral line radio astronomy measurements, the signal of interest is normally in one sideband, so it is desirable to suppress atmospheric noise entering the receiver in the image band. The image rejection R_b, defined in Fig. 6(b), is therefore the relevant quantity. To measure R_b accurately using an RF signal generator would require an accurate knowledge of the relative signal levels entering the receiver when the generator was tuned to the upper and

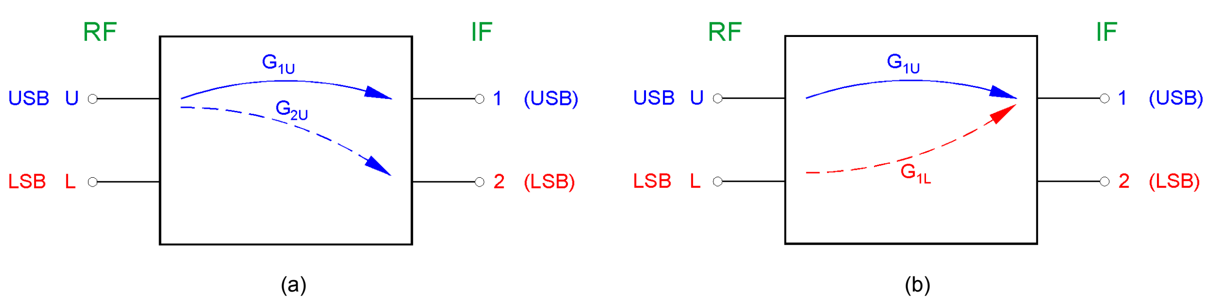

Fig. 6. Two definitions of image rejection. (a) Image rejection $R_a = G_{1U}/G_{2U}$. (b) Image rejection $R_b = G_{1U}/G_{1L}$. In the context of radio astronomy, (b) is the appropriate definition.

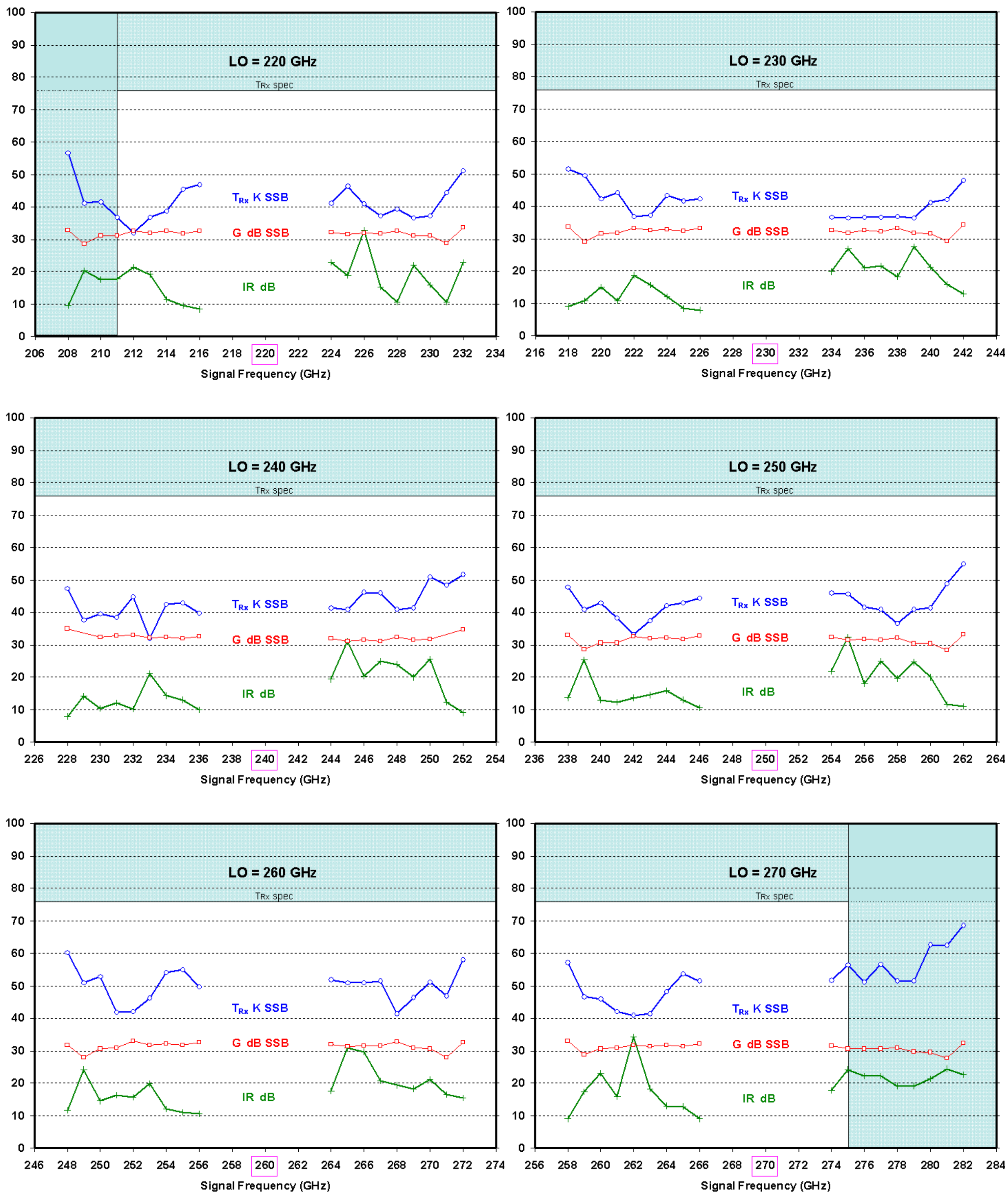

Fig. 7. Measured SSB noise temperature, gain, and image rejection for the complete sideband-separating receiver with the mixer-preamp at 4.2 K. Each frame is for the LO frequency indicated. The upper and lower sideband data are shown as functions of signal frequency over the range corresponding to the 4-12 GHz IF band.

lower sidebands. Relative signal levels are difficult to measure within ± 3 dB at millimeter wavelengths, especially with the high IF (4-12 GHz) for which upper and lower sideband signals can be as much as 24 GHz apart. The need to know the relative signal levels is avoided if additional measurements are made with two well matched spectrally flat noise sources with different noise temperatures — *e.g.*, the hot and cold loads used for measuring the receiver noise temperature. This is described in ALMA Memo 357 [18].

Using the standard procedure for measuring the noise temperature of a millimeter-wave receiver, hot (room temperature) and cold (liquid nitrogen) loads are placed in front of the receiver. This gives the receiver gain and noise temperature at each IF output, uncorrected for image rejection. The quantity $M_{DSB} = (P_{hot} - P_{cold})_{IF\ port\ 1} / (P_{hot} - P_{cold})_{IF\ port\ 2}$ is calculated. Then, a small CW test signal is applied at corresponding upper and lower sideband frequencies $f_{LO} + f_{IF}$ and $f_{LO} - f_{IF}$. The change in IF output powers at IF ports 1 and 2, ΔP_1^{USB}, ΔP_2^{USB}, ΔP_1^{LSB}, and ΔP_2^{LSB}, when the source is switched on is measured. For the CW source in the upper sideband, the quantity $M_U = \Delta P_1^{USB}/\Delta P_2^{USB}$ is calculated, and for the CW source in the lower sideband the quantity $M_L = \Delta P_1^{LSB}/\Delta P_2^{LSB}$ is calculated. The relative CW source powers in the upper and lower sidebands need not be known. The image rejection at each output is then given by [18]

$$R_1 = M_U \cdot \frac{M_L M_{DSB} - 1}{M_U - M_{DSB}} \quad \text{and} \quad R_2 = M_L \cdot \frac{M_U - M_{DSB}}{M_L M_{DSB} - 1} .$$

The measured noise temperatures and gains are then corrected for the image rejection to give the true single sideband quantities. Figure 7 shows the measured SSB noise temperature, gain, and image rejection for the complete receiver. Each frame is for the LO frequency indicated, and the upper and lower sideband data are shown as functions of signal frequency over the range corresponding to the 4-12 GHz IF band.

DISCUSSION

The SSB receiver noise temperatures were < 50 K (< 4.5hf/k) over most of the band and < 60 K across the whole of Band 6 (211-275 GHz). The image rejection was > 10 dB except at a few isolated frequencies where it was as low as 9 dB — sufficient to give effective suppression of unwanted atmospheric noise in the image band. The mixer-preamp gain was 32 ± 3 dB, and at any given LO frequency the gain variation was ± 2 dB across the 4-12 GHz IF band. All gains and noise temperatures are for the complete receiver and are referred to the receiver input outside the vacuum window. The measurements were made with the mixer-preamp heated to a physical temperature of 4.2 K as required for ALMA testing (the temperature at the cold stage with the heater off was 3.5 K).

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