A Prototype Focal Plane Array with HEB Mixer Elements and MMIC IF Amplifiers

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ABSTRACT

We describe the design, construction and testing of a 3-element prototype focal plane array (FPA) based on HEB superconducting mixers and wide-band MMIC IF amplifiers. This prototype is the first functional heterodyne FPA to be reported for any frequency above 1 THz. The FPA module makes use of a quasi-optical coupling scheme and incorporates all bias and IF circuitry in the same housing, resulting in a fairly compact design, with the MMIC amplifiers placed in the same plane as the HEB devices. We present novel experimental results regarding noise temperature and coupling efficiency of this array. We also discuss how the number of pixels can be enlarged considerably in the future by using a multi-level array architecture.

1. INTRODUCTION

The development of Hot Electron Bolometer (HEB) technology over the past decade has made possible the implementation of single-pixel observing platforms operating at terahertz frequencies. Instruments such as TREND, TELIS, GREAT, and HIFI, are current examples of heterodyne receivers based on this technology. Similarly, cryogenic IF amplifiers have evolved over the last two decades from GaAs Field Effect Transistors (FETs) to High Electron Mobility Transistors (HEMTs) and more recently to InP HEMTs [1]. Advances in modelling and fabrication technologies have brought forth Microwave Monolithic Integrated Circuit (MMIC) Low Noise Amplifiers (LNAs) with remarkable noise performance and low dc-power consumption [2]. In order to exploit the benefits of these ongoing technological efforts even further, it is worthwhile to consider the integration of HEB mixers and MMIC amplifiers into focal plane arrays. Such integration yields a substantial improvement in detection speed compared with single-pixel receivers. The low LO power consumption and near quantum noise limited performance of HEB mixers make them well suited for integration in multi-pixel FPAs.

We have developed a three element array based on the fly's-eye concept, as illustrated in Figure 1, where each detector element is placed in the focal plane of an objective lens or reflector. The implementation of the fly's eye concept utilizing HEB array receivers and MMIC amplifiers, was proposed in [3]. All the required DC-bias and RFI protection circuitry, are accommodated inside a split-block design that uses field-replaceable SMA connectors to extract the IF outputs for each pixel. The focal plane array prototype was designed to operate at 1.6 THz but can operate at any terahertz frequency by changing the design center frequency for the integrated antennas. This HEB FPA is fully operational and represents the state-of-the-art in receiver technology for terahertz frequencies.

2. DESIGN CONSIDERATIONS

Figure 2 illustrates the basic configuration for a single element in the array. This design is based on a single element receiver we have developed previously [4].

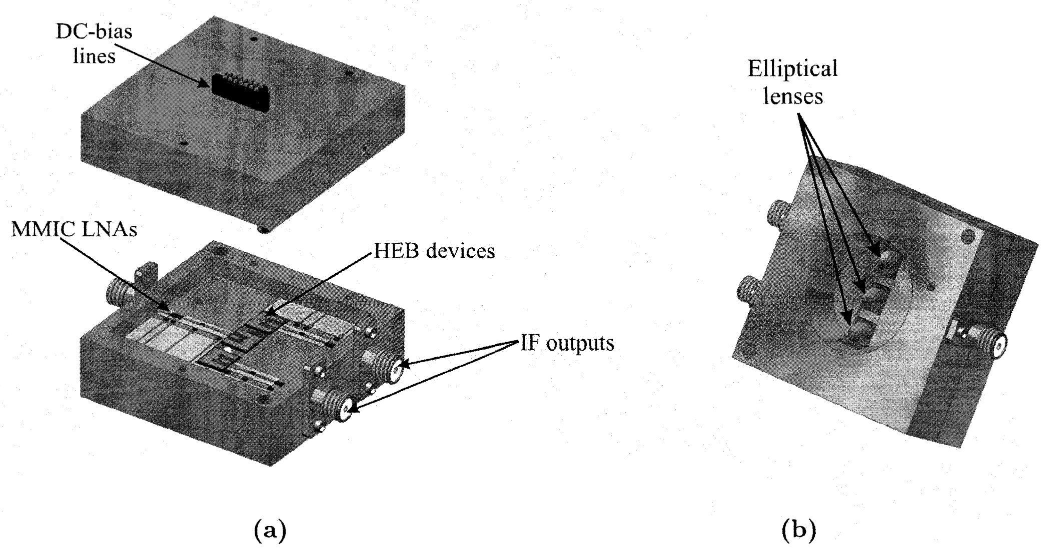


Figure 1: Concept for the 3x1 FPA: (a) Inside view; (b) Lens side.

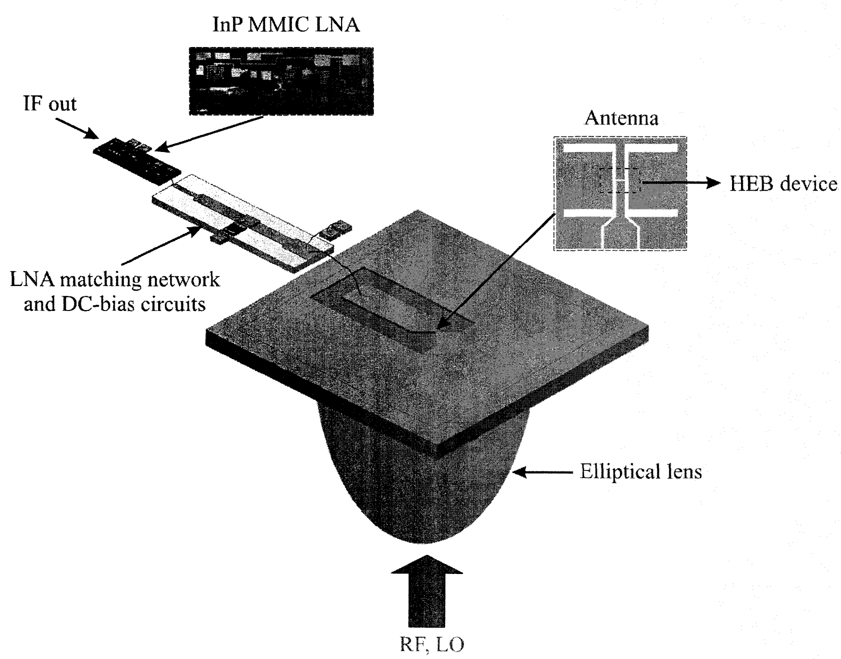


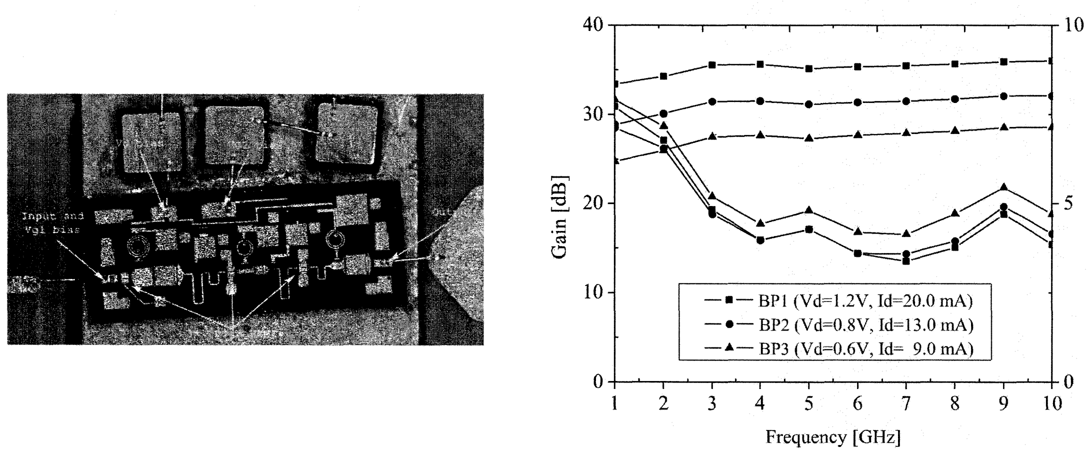
Figure 2: Concept of an integrated single-element THz receiver.

2.1 Quasi-Optical Considerations

We use a quasi-optical scheme to couple the incoming radiation to the detector, consisting of a silicon elliptical lens and a monolithic antenna. This configuration of a single pixel receiver was analyzed in [5] and [6]. Multipixel receivers for lower frequencies with a similar fly's eye configuration were described in [5] and [7]. A major advantage of this configuration is that it allows ample space for IF amplifiers, transmission lines, and bias lines. The active elements we use are phonon-cooled NbN HEBs fabricated on a 350 μm thick silicon substrate. The device chip size is 6 x 6 mm. We have previously developed a fabrication process for near quantum noise limited HEB devices integrated with either twin-slot or slot-ring antennas [8]. Both types of antennas were designed and tested at 1.6 THz.

2.2 MMIC IF Amplifiers

The MMIC chip utilized in our prototype was originally intended for use on the Allen Telescope Array [9]. It was developed and tested by Sander Weinreb and Niklas Wadefalk at JPL/Caltech. This amplifier (referred to as WBA-13) has three stages of InP transistors with 0.1 μm gate length, demonstrated gain of about 10 dB per stage and total noise temperature of less than 8K throughout the 1-10 GHz band. Figure 3a shows a picture of the MMIC chip (size 0.75 x 2 mm). The three capacitors shown on top are the pads for DC-bias of the transistors. Both the input and output pads are wire (ribbon) bonded to microstrip transmission lines placed at either end of the circuit. As can be seen in Figure 3b, the noise temperature of the WBA-13 is remarkably low and nearly independent of bias settings. This feature allows minimizing the power dissipation without paying the price in the total receiver noise temperature. Power dissipation will become a restrictive issue as the number of elements in the array becomes large.



(a) (b)

Figure 3: WBA13 MMIC amplifier: (a) Close-up view of the chip; (b) Performance of the MMIC measured at 11K for different bias conditions.

2.3 MMIC/HEB Impedance Matching

In general, the impedance that a phonon-cooled HEB will present to the IF circuitry will be complex, yet predominantly real for frequencies below the *IF gain bandwidth*, i.e. the IF frequency at which the conversion efficiency of the mixer drops by 3 dB from its low IF value [4]. This IF impedance has been found to follow the differential slope in the IV curve for a particular bias point [4], [10]. Therefore the device impedance may be changed through the proper combination of LO power and DC voltage.

Consequently, it is reasonable to assume that the IF impedance of the HEB is close to 50 ohms, at least over the bandwidth of interest and in the vicinity of the optimum bias point. A multi-section matching transformer fabricated on microstrip line was placed at the input of each WBA-13 chip so that the impedance of the HEB is matched to the capacitive reactance presented by the MMIC input gate (see Figure 2).

2.4 DC-Biasing

The DC-biasing scheme for the HEB mixers in the FPA is a variation of the 4-wire concept used in the TREND instrument [11]. The matching network described in subsection 2.3 includes a series DC-blocking chip capacitor, which in conjunction with an RF-blocking spiral inductor, forms a broadband bias-tee for each mixer. A 50 kΩ resistor is used in order to inject the appropriate gate voltage to the first HEMT stage. Additional chip resistors are placed on a separate circuit board to monitor the voltage and current signals from the device, as well as for protection of the MMIC chips. A number of chip capacitors are soldered onto the same board to provide protection against RF interference and shunt transients to ground. All three elements are biased simultaneously using dedicated electronic circuitry interfaced using a computer running Labview® software.

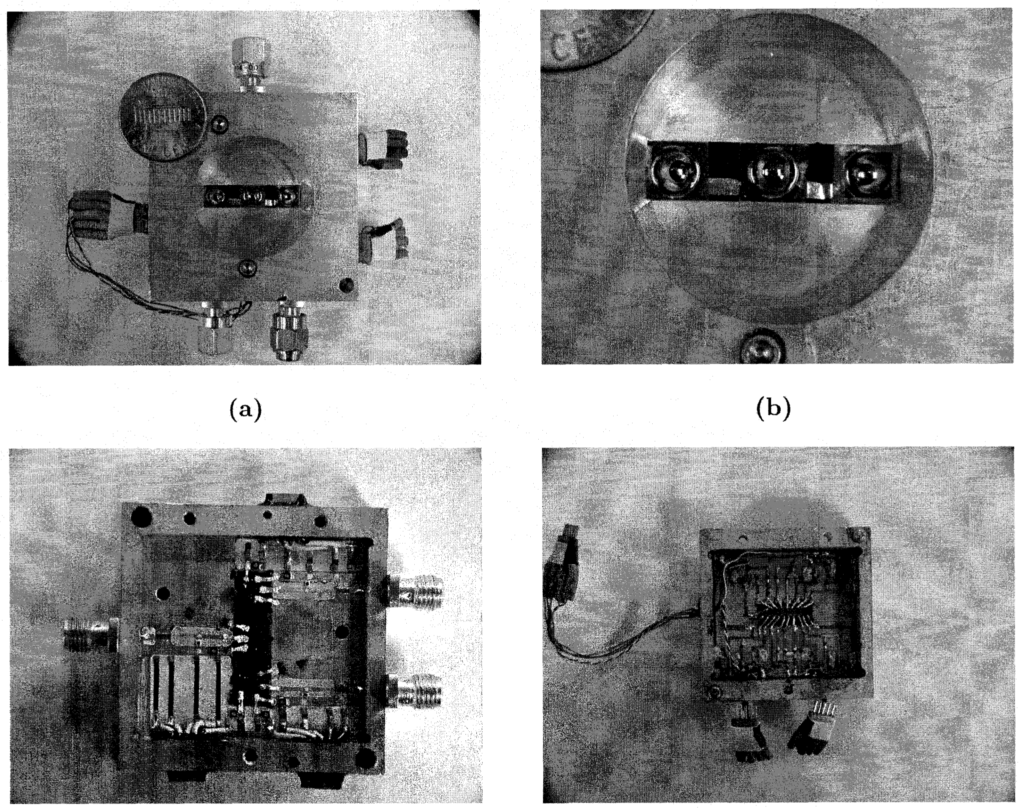
3. FPA PROTOTYPE

The designed split-block structure was machined from OFHC copper (size 4.5 x 4.5 x 2.5 cm). All three MMIC amplifiers, silicon device chips and associated components were assembled together as shown in Figure 4. The spacing between elements was chosen to be 8.5 mm (Figure 4b) in order to avoid any interaction between radiating elements. The minimum possible spacing will be limited by diffraction effects [12], and will be investigated further in the future. The front half of the block (Figure 4c) contains part of the bias circuitry as well as the MMICs and the HEB devices, which were thermally contacted to the metallic block using small amounts of Stycast®. The electrical connections to the rest of the circuit were made using indium ribbon. Each MMIC was enclosed in a narrow rectangular cavity in order to minimize cross talk between amplifiers. The cavity is designed to have a cut-off frequency well above the maximum frequency of operation of the MMIC (75 GHz in this case). The input/output microstrip lines were not covered with a metallic structure. Instead, we used Eccosorb® microwave absorber to avoid exciting waveguide modes inside the block. These undesired modes lead to feedback effects that would otherwise drive the MMICs into oscillation.

All bias connections are routed from the front to the back half of the block (Figure 4d) using three multi-pin connectors. The back half of the module contains a circuit board with surface-mount components for DC-biasing. One main DC-connector located outside of the FPA provides the final interface to the liquid helium dewar wiring.

4. EXPERIMENTAL SETUP

Two different sets of tests were performed in order to characterize the noise temperature and optical coupling to the array elements. The LO source was a CO_2 laser pumped far-infrared (FIR) gas laser, operating on a 1.63 THz line in difluoromethane (CH_2F_2) gas with a typical power output of 30 mW. The power was injected through a six micron thick mylar beam splitter. We found that we had enough LO power to pump the three detectors simultaneously. This was achieved by defocussing the laser beam until it covered all elements. There are only two coaxial lines in our dewar. We were, therefore, unable to measure all three elements simultaneously. The noise temperature measurements were performed using the Y-factor method, where a hot/cold blackbody source is inserted into the signal beam path and the change in IF power is recorded [4]. The optical test was performed using sideband techniques, as described in [13]. An Offset-Axis Parabolic (OAP) reflector was used as the last focusing element. This mirror was mounted on a linear translator such that its vertical position could be moved. The incident beam to the OAP was the input signal, and this beam had been collimated to form a long waist. The OAP could thus be translated vertically while keeping the signal beam focused in the aperture plane of the two silicon lenses in the FPA, inside the cryostat.



(a) (b)

(c) (d)

Figure 4: The three element FPA: (a) Seen from the lens side; (b) Close view of the lens side; (c) Inside of the front half; (d) Inside of the back half.

The FPA was mounted in the cryostat such that the two elements (designated A and C, respectively) were along the z-axis. The output signals from the two detectors under test were recorded on a spectrum analyzer. We used a convenient IF frequency of 2 GHz.

5. RESULTS AND DISCUSSION

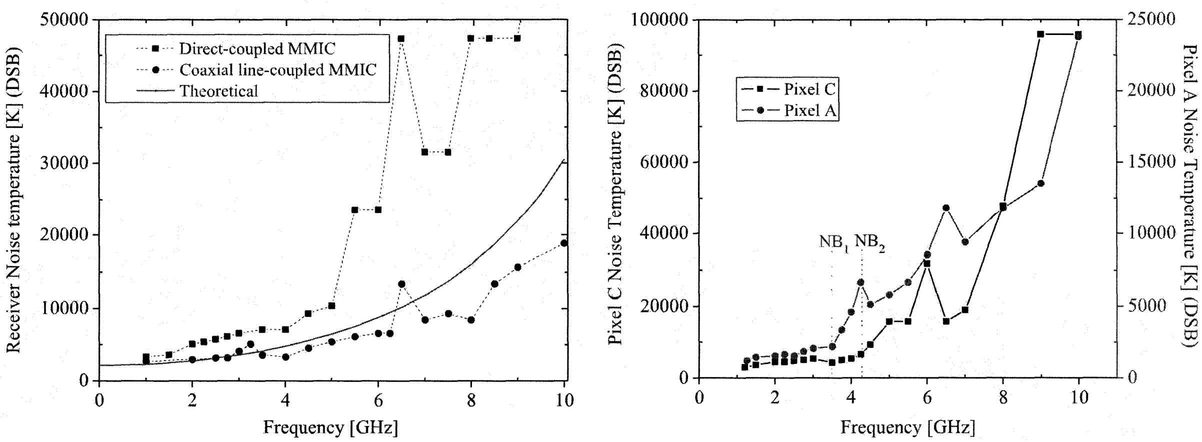
We first performed noise measurements on one device installed in the FPA. This HEB device had been measured previously with the HEB device and the LNA on a separate module and connected through a short coaxial transmission line. The new configuration with the HEB much closer to the MMIC produced a different response, as can be seen in Figure 5a. The receiver noise temperature is essentially the same below the *noise bandwidth*[1] in both cases. The broadband matching of the HEB to the MMIC was affected by the FPA environment, causing a faster rise of the total noise temperature as the frequency grows. Nevertheless, we have successfully integrated an HEB and an MMIC in the same block for the first time and measured comparable noise temperatures over the useful bandwidth of the mixer.

In the next step, two HEB devices coupled with twin-slot antennas were measured simultaneously in the FPA unit. One element had a noise temperature of 1,200 K while the noise temperature of the second element was about 3,000 K, both at 1 GHz IF, as shown in Figure 5b[2]. The more sensitive device had a noise bandwidth of about 3.5 GHz (NB_1), versus 4.25 GHz (NB_2) for its counterpart.

[1]The frequency at which the noise temperature doubles with respect to its low frequency value [4].

[2]The second device had earlier been measured to have a similar noise temperature but had degraded.

The differences between the two elements are not unexpected since the IV characteristics were different. This is often due to NbN film inhomogeneity and fabrication issues. The final three element FPA module included a slot-ring device as the third detector. This specimen is expected to have a noise temperature of 2,000 K according to its IV characteristics.



(a) (b)

Figure 5: Measured IF response of the FPA: (a) Single element response; (b) Two elements pumped simultaneously.

Next, we performed the optical test using the general approach outlined above. The output power for both elements was recorded on a spectrum analyzer as the OAP displaced the signal beam along the z-axis. The data for this test are shown in Figure 6. The output powers were normalized to their respective peaks and are plotted on a linear scale. The dotted curve represents the expected response of the third element.

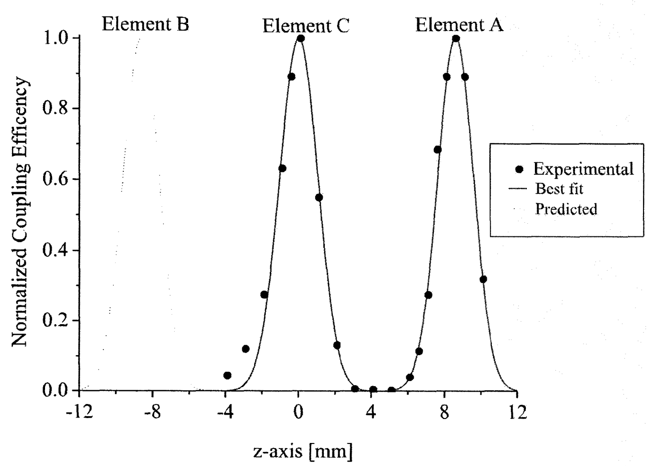


Figure 6: Measured response of two adjacent elements in the FPA.

We simulated the beams assuming a Gaussian shape for both the input sideband and the response of the individual elements. The Gaussian beam waists are assumed to be the same, as would be the case if the sideband were optimally focused on the elliptical lenses for the two FPA pixels. In the simulations we varied the Gaussian beam parameter, w, until a best fit to the measured data was obtained. This procedure produced a value for w very close to what we had calculated previously for the particular lens/antenna configuration, about 1.5 mm (see solid curve in Figure 6). The quasi-optical response is predicted to have a "Gaussicity" of about 94 %. The spacing between the two detected peaks also agrees well with the actual separation of the lenses, 8.5 mm. Furthermore, our simulations allowed us to estimate the minimum possible separation between contiguous pixels for future FPAs of this kind to be 4.25 mm.

6. CONCLUSIONS AND FUTURE WORK

We have designed, constructed and tested the first heterodyne focal plane array for any frequency above 1 THz. The design integrates three elements composed of MMIC IF amplifiers and NbN phonon-cooled HEBs. Isolators were not used in this design, which considerably reduced the size of the prototype. We showed the efficacious integration of an MMIC and an HEB for the first time. Very good noise temperatures were measured for low IF frequencies. Future investigation of the broadband matching mechanisms will allow us to extend the useful bandwidth of the receiver. We have successfully tested the optical coupling of contiguous elements in the FPA. The measured response showed a very good agreement with the theoretical prediction. The array presented here can in principle be extended to a larger number of elements. A large planar array, though, would lack adequate space for complete IF and DC-bias circuits and will present potential difficulties in thermal power dissipation [14]. To overcome these problems, we propose a multi-level architecture as illustrated in Figure 7. The lenses can be stacked with small clearance producing diffraction limited resolution. The device board consists of the HEB devices at the terminals of the antenna structure. The connections to the IF board above are done using indium bumps connected to the MMIC amplifiers through via holes. The bias board uses spring-loaded pins to contact a number of points in the IF board, thus providing the required bias voltages for both the HEBs and the IF amplifiers. All boards are assembled using special alignment pins. Future work will address all the issues and fabrication techniques involved in realizing this array architecture.

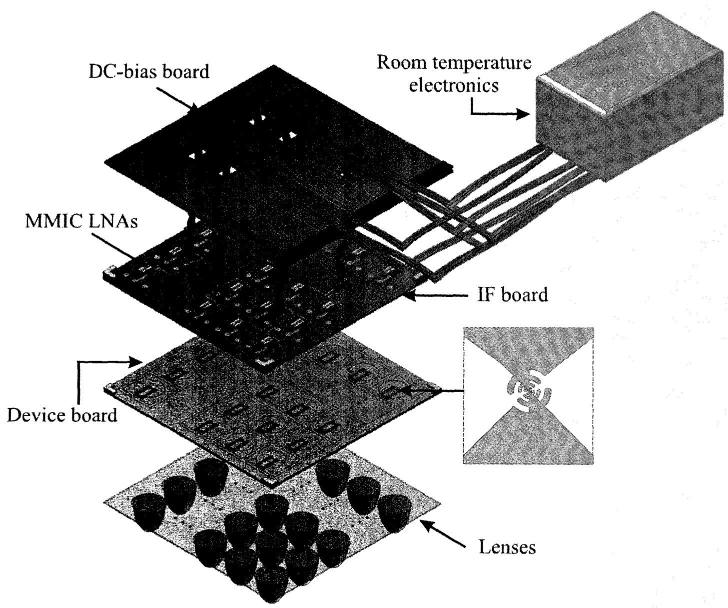


Figure 7: Conceptual focal plane array architecture with HEB devices.

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