Amplifier Arrays for CMB Polarization

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ABSTRACT **Cryogenic low noise amplifier technology has been successfully used in the study of the cosmic microwave background (CMB). MMIC (Monolithic millimeter wave integrated circuit) technology makes the mass production of coherent detection receivers feasible. We have produced large numbers of MMIC amplifiers for CMB measurements. We have also demonstrated the viability of multi-function multi-chip modules as sensitive receiver front-ends. MMIC integration makes it possible to realize massive arrays of receivers suitable for measurements of the polarization of the CMB. We describe the development of the unit cell of such an array and the development plans for implementation.**

I. Introduction

Amplifier technology has been used in the measurement of the anisotropy of the cosmic microwave for several decades. Cryogenic high electron mobility transistors (HEMT), ideally suited for millimeter-wave CMB receiver front-ends, have been demonstrated with noise as low as 5 times the quantum limit. Examples of experiments using this technology to return important scientific data include COBE, UCSB ACME, HACME and BEAST telescopes, CBI, DASI and WMAP [1-5]. It is reasonable to expect that the same technology will be used to make sensitive CMB polarization measurements. Indeed, DASI has already measured the E-mode polarization of the CMB and CAPMAP will likely detect polarization at smaller angular scales [6,7] .

Indium Phosphide (InP) transistor technology has been successfully integrated with monolithic millimeter wave integrated circuit (MMIC) technology, providing for passive amplifier elements, to produce state-of-the-art amplifiers at frequencies up to 120 GHz. MMIC technology is ideally suited to mass production of low-noise receiver front-ends, with reduced assembly time and a high level of chip integration. Prototype development for the Planck-Low Frequency Instrument (LFI) has shown that MMIC amplifiers can be integrated into compact modules with several radiometer functions, without sacrificing performance.

We will show how this technology can be employed in the fabrication of massive polarimetric arrays, using existing semiconductor packaging techniques, adapted to millimeter wavelengths.

II. InP HEMT Technology

Field Effect Transistor amplifiers have been used in radio astronomy for decades. Advances in technology which have led to substantial improvements in performance include molecular beam epitaxial growth, leading to conduction channels with high mobility; development of sub-micron gates using electron-beam lithography; materials advances such as InP substrates with high In content channels and MMIC integration, reducing the parasitic effects of bonding pads and wires at high

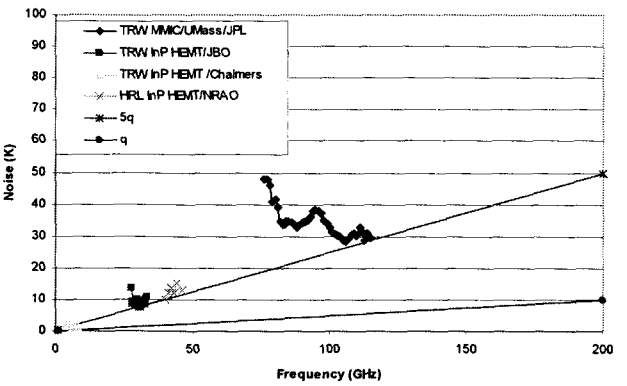

Figure 1. Current state-of-the-art for low noise cryogenic amplifiers. The data are shown relative to one and five time the quantum limit.

frequencies.

Cryogenically cooled low noise amplifiers are the receiver front-end of choice for frequencies 1 to 110 GHz. They have very broadband operation, optimum operation at 20K, operate at room temperature for testing and have the best noise figure at frequencies below 100 GHz. A current plot of amplifier performance is shown in Figure 1[Compiled from several sources].

Since they preserve the phase of the incoming signal, the noise of an amplifier is limited by quantum

mechanics. The quantum limit for noise is given approximately by the equation:

$$T_{sys} \geq h\nu/k_B$$

At frequencies below 50 GHz the quantum limit is less than the 2.7K CMB, and the performance hit for using amplification is not considerable.

Figure 1 shows amplifier performance relative to the quantum limit. Most of the amplifiers in the figure lie along the 5q line. One exception to this is the amplifier at 8 GHz which has a noise ~3q.

The amplifier shown in Figure 2a is an InP MMIC produced by Northrop-Grumman Space Technology (formerly TRW) [8]. It is ideally suited to mass production and array implementation. The amplifier has been used in the CAPMAP polarization experiment, the 16 element SEQUOIA I & II arrays [9], and will be used in the AMiBA and SZA experiments.

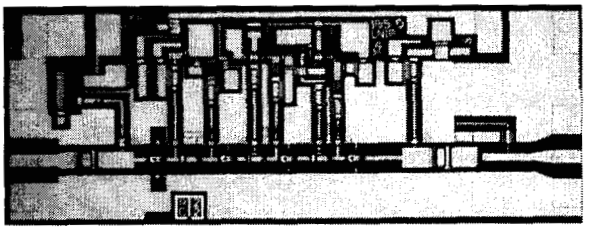

Figure 2. 65-110 GHz InP MMIC low noise amplifier. The size of the chip is 2100x850 microns.

III. POLARIMETER DESIGNS

Although there is a raw noise penalty to be paid for using coherent detection, relative to bolometric direct detection, the technology offers several advantages from a systematics point of view, and when utilized in a well designed receiver, the penalty is minimal.

Polarization is a coherent property of radiation, defined by the relative amplitude and phase of two orthogonal linearly polarized waves. The relative phase can be measured by lagging one of the waves and summing or multiplying. The amplified signal can be divided and several lags can be applied without input signal loss.

Synthetic aperture interferometers such as DASI and CBI, have N elements each viewing the same solid angle Ω_f. If each of the elements in the array is pairwise multiplied, the synthesized image will have a solid angle Ω_f with angular extent $\theta_f \propto \lambda/d$ (for a 2 dimensional symmetric array), where d is approximately the individual antenna aperture, and a resolution θ_b, where $\theta_b \propto \lambda/D$, with D being the largest separation parallel to the synthesized beam.

Since each receiver views the entire field of view, all signals pass through all amplifiers and pick up the same systematic gain fluctuations. Upon multiplication, only correlated signals remain. If the input polarizer selects *circular polarization*, both linear polarizations pass through the same amplification chain, allowing stable relative measurements of linear polarization. The synthetic aperture interferometer is thus capable of making simultaneous measurements of the I, Q and U Stokes parameters.

The synthesized image is the Fourier Transform of the cross-correlation as a function of the two

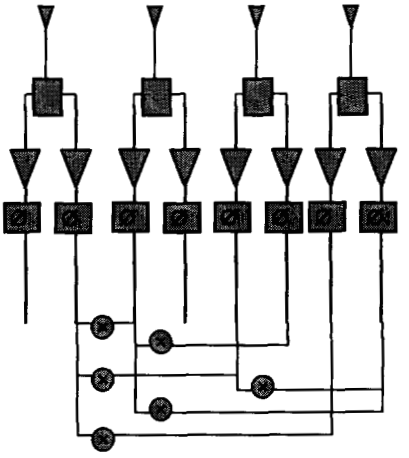

Figure 3. Schematic of an interferometric array receiver. The feed antennas have diameter d and separation D.

dimensional separation, or the visibility function. Since the synthesized image is the Fourier transform of the visibilities, every correlated pair adds noise as the quadrature sum of the individual correlator noises, while adding signal linearly [10]. A minimally filled array will therefore have signal unity (in temperature units) for each synthesized beam and a noise of $N*T_{sys}/\sqrt{\beta\tau}$. With each new radiometer added within the array area, N redundant baselines are introduced, the noise then drops as 1/N. The sensitivity of the 2-d array is given approximately by:

$$\Delta T = (\Omega_f / \Omega_b N) * T_{sys}/\sqrt{\beta\tau}$$

For $N >> 2*D/d$. The factor in front of the familiar radiometer equation is simply the area "fill factor" of the array.

The primary technological challenge associated with large N synthetic aperture arrays is the signal multiplier or correlator. N(N-1)/2 separate multiplications are required to utilize all available information. If N is large, and in-phase and quadrature-phases are multiplied, N^2 correlations are required. For practical interferometers, the bandwidth is limited by "fringe washing" or varying phase delay with frequency, to a few percent of the center

frequency. This means that in addition to the N^2 problem, the number of correlations must be multiplied by an additional factor ~10. A hypothetical 30 GHz interferometer with β=10 GHz and N=100 requires 10^5 correlations each with 1 GHz bandwidth. This is a factor of 100 more ambitious than that used by DASI and CBI.

One can alternatively use correlation on a single

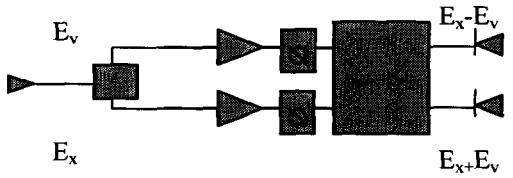

Figure 4. Correlation polarimeter. The signal enters the feed horn at the left side. The linearly polarized OMT passes signals to the amplifiers. The output hybrid signal combiner and diodes serve to multiply the input signals. The radiometer is sensitive to U Stokes parameter.

pixel to build a stable polarimeter. CAPMAP, PIQUE, POLAR and COMPASS and KuPID [11] all use a linearly polarized orthomode transducer (OMT) as a polarization "splitter". A 45° linearly polarized wave entering the receiver in Figure 4 will be split equally into each of two amplification chains. Multiplication of these amplified signals yields a net output. Alternatively, if the incoming signal is 0°, 90° or unpolarized, no signal is obtained. This radiometer is therefore sensitive only to the "U" Stokes parameter, $<E_xE_y>$.

An alternative design has the input polarizer accept circular polarization, splitting each linear polarization and putting a phase lag between them. The radiometer in Figure 5 has both linearly polarized states being amplified in both chains. If the resulting signals are multiplied, the output is E_x^2-E_y^2, or Stokes "Q" parameter. If a 90° phase shift is applied to one leg and then the signals multiplied, the "U" Stokes parameter again results. Since the signal has been amplified, both operations can be carried out with no loss of signal to noise. This receiver design has been proposed for SPOrt [12].

The sensitivity of the correlation receiver is given by :

$$\Delta T=\sqrt{2}* T_{sys}/\sqrt{\beta\tau}$$

where $\Delta T= (T_x-T_y)=2Q$, by definition. If more radiometers are added to the array, each viewing a different part of the sky, as is the case in a focal plane array, and the optical system is scanned to cover a solid angle Ω_f with a beam solid angle Ω_b, the map sensitivity is given by:

$$\Delta T=\sqrt{2}* T_{sys}/\sqrt{(\beta\tau N\Omega_b/\Omega_f)}$$

Now the sensitivity goes as the square root of the fill factor. This is a substantial improvement for fill factors less than unity. It is interesting to note that the sensitivity for both the interferometer and the filled aperture array are identical for unity fill factor [Halverson, 2002], although there are fundamental practical limitations in ever achieving this condition.

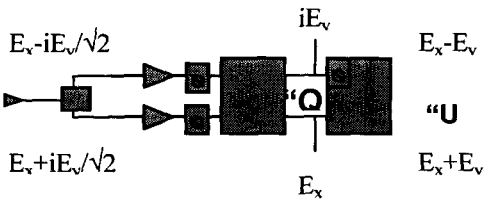

Figure 5. The Q and U correlation polarimeter. The signal entering from the left, passes through a left-right circularly polarized OMT, passing all orientations of linearly polarized light through both amplifiers. The first hybrid coupler outputs pure horizontal and vertical components, the difference between which is Q. The second hybrid and subsequent detectors, serves to multiply the horizontal and vertical components, delivering U.

IV. INTEGRATED POLARIMETERS FOR ARRAYS.

Using the MMIC technology described in section II, it is possible to realize inexpensive, mass producible polarimeters suitable for array implementation.

Correlation receivers of the type described in Section III, have been expensive and tedious to fabricate. Typically the cold-low noise front end has been combined with a warm back-end through a waveguide connection, usually phase sensitive. Connectors and cables limit the number of bias leads available to exercise the necessary degrees of freedom to obtain adequate gain and phase matching. This necessitates tedious manual tuning of each component.

We can take a cue from the semiconductor industry and integrate as many functions as possible on a single chip, reducing interconnects, but bringing out all necessary bias and DC signals, but this can also be problematic. If the antenna structure is integrated on the wafer, it will dominate the wafer area. Since high-performance semiconductor processes are still not inexpensive, this is a costly waste of space. Similarly some of the components necessary for the polarimeter are best fabricated on disparate processes.

A second lesson can be taken from the semiconductor industry; multichip module integration.

Mass production of such parts has been enabled by automated die attachment and wire bonding equipment. Such machines are readily available with the accuracies required for MMIC parts at frequencies upward of 100 GHz. A mass-producible polarimeter will ideally take advantage of these technologies.

Figure 6 shows a CAD drawing of the layout of a "plug-in" style polarimeter operating at 90 GHz. The input is a pair of waveguides coming from an OMT polarizer. The output is the voltage on a pair of detector diodes. All bias signals are brought in through the pins. With 20 pins in the module, there are adequate contacts to perform all of the necessary optimization.

The assembled module, operates as an IC "chip" polarimeter, ideally mounted on a printed circuit board. All necessary signal conditioning and control components can be located on the board at or near room temperature. This means that standard silicon components may be used to control the units and read out data. The design is thus inherently scalable. Computer interfaces to the control components allow for automated tuning of the individual polarimeters, critical if a large number are to be built.

No technological barriers exist to the development of such a polarimeter. Indeed, all of the critical components, MMIC amplifiers and phase switches have been developed under Planck-LFI. The LFI also showed that a large number of chips with substantial gain (50 dB), can be integrated into a single cryogenic package.

The module in Figure 6 is currently in fabrication. We expect a prototype demonstration in the lab by October 2003 and a field test of a few elements by January 2004. The initial polarimeters will be sensitive to only one Stokes parameter. With a receiver noise of 45 K, a sky noise of 12 K , CMB photon noise, and a bandwidth of 15%, we expect an instantaneous noise of 425 $\mu K\text{-}\sqrt{s}$ per Stokes parameter.

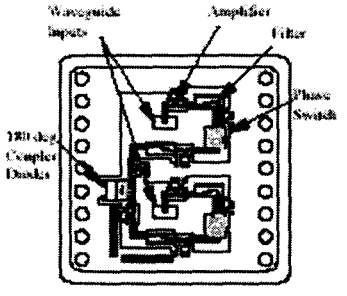

Figure 6. Compact polarimeter module concept. The module shown has all of the functionality of a U polarimeter described in Figure 4, except for the OMT. The size is one inch on a side.

Since the polarimeter is designed for automated assembly from the outset, we expect to have a 91 element array fabricated by Fall 2004 and even larger arrays a year after that. The 91 element array, with sensitivity to Q and U in each pixel and 20% bandwidth, will have an instantaneous sensitivity of 36 $\mu K\text{-}\sqrt{s}$ per Stokes parameter in both Q and U.

V. Conclusion

We have described the state-of-the-art in amplifier technology. The relative sensitivity of different receiver architectures has been explored in terms of raw mapping speed. Finally, we have shown that it is possible to fabricate low-cost massive arrays of MMIC polarimeters using existing technology and extensive use of automatic assembly and test.

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