COHERENT DETECTORS

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EXECUTIVE SUMMARY

Coherent detectors offer many advantages for CMB polarization measurements due to the fact that the full phase and amplitude information in the incoming signal is available for multiple uses in later signal processing. Some of these advantages give increased control of systematics, others give simpler systems. Operation at 20 K rather than ~ 0.1 K also results in simpler systems.

The cost of preserving the phase of the incoming signal is quantum noise, which is proportional to frequency. Whether qantum noise is a serious and limiting problem for coherent detection of CMB polarization depends on the answers to two critical questions: What frequency range is required for accurate foreground removal in CMB polarization observations? How close to the quantum limit can amplifiers come?

The first question remains open because we don't have accurate enough information about polarized foregrounds to support realistic simulations, but if the dust spectrum is complicated a top frequency of 150 or 200 GHz may be optimum. (This question is under consideration by a separate activity of the mission concept study.) The answer to the second question has changed significantly over the last few years, and the path seems clear to achieving noise within a factor of 2 or 3 of the quantum limit up to 150 GHz, maybe higher. Up to at least 150 GHz, and perhaps higher, experiments based on amplifiers should be able to achieve the noise levels recommended by the TFCR in space within a few years. Such experiments would be significantly less expensive than experiments based on bolometers. The active cooling requirements at 20 K for such experiments could be met with existing technology in space. If observations at frequencies much higher than 150 or 200 GHz are required for control of systematics, adequate noise levels will be hard to achieve with amplifiers.

On the ground, coherent systems maintain the same advantages in practicality and control of some systematics, but have significantly lower noise than bolometer systems.

The ultimate control of systematics is afforded by coherent interferometers. Rapid development of correlator technology driven by commercial forces has made it possible to correlate hundreds of elements in space for easily affordable power.

The TFCR recommended:

- "Technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors.. . .It is important to keep open a variety of approaches until a clear technological winner has emerged."
- "A strategy that supports alternative technical approaches to detectors and instruments. Advances in CMB science have been based on a variety of technologies. Though we expect that bolometers will be the clear choice for CMBPOL, it is premature to shut down the development of alternatives. We recommend the continued development of HEMT-based detectors as they might lead to an alternative space mission and will certainly be used in ground-based measurements."

The noise projected for amplifier systems has changed dramatically since the TFCR deliberated, when the expectation for amplifier noise at 140 GHz was too high to list in their table. This elevates the importance of the TFCR recommendation to support multiple approaches including HEMT-based detectors. Transistors now exist that far exceed the performance of anything that existed or was projected in 2005 at millimeter-wave frequencies.

- A downselect of detector technology should not be made before foregrounds are better measured, or before all new technologies required for either bolometer or amplifier missions have been demonstrated in suborbital experiments and shown to be suitable for CMB work.

1 INTRODUCTION

In this paper we review the status and promise of coherent (phase-preserving) detection systems for measurements of CMB polarization, and outline the scope and scale of the development program that would be required to realize the promise of the technologies involved. We consider both large arrays of independent continuum detectors looking at the sky through feeds or telescopes, as well as interferometers, in which signals from different elements are correlated. Low-noise amplifiers are common to both approaches. Inteferometers require in addition local oscillators (LOs), mixers, and correlators.

Transistor performance has improved dramatically over the last 20 years, driven primarily by military and civilian communication requirements at room temperature. High-electron-mobility transistors (HEMTs) offer low noise, low power dissipation, high reliability, inherently wide bandwidths, insensitivity to electromagnetic and charged particle radiation, the ability to handle high signal levels without damage, and operation over a wide temperature range. Transistors are not the only possible active element. SIS mixers have extremely low noise, and are still in widespread use for spectroscopy and interferometry at frequencies $> 100\,\mathrm{GHz}$ or so. However, it is difficult to achieve the 20–30% fractional bandwidths needed for CMB work with SIS mixers. As a result, *we will restrict our attention to amplifiers only.*

The theoretical sensitivity of a "total power" radiometer array of N identical elements (to a signal filling the beam or in surveying the sky) is given by

$$\Delta T_{\rm min} = \frac{T_{\rm sys}}{\sqrt{N\beta\tau}} \tag{1}$$

where $T_{\rm sys}$ is the system noise temperature, β is the RF bandwidth of the radiometer, τ is the post-detection integration time, and $\Delta T_{\rm min}$ is the minimum detectable signal in that integration time. The sensitivity of other radiometer designs is of the same form, but with additional factors of order unity. Clearly there are three basic ways to make a more sensitive radiometer: 1) reduce the noise $T_{\rm sys}$; 2) increase the bandwidth β; or 3) increase the number of "pixels" N.

The path to improved sensitivity, therefore, is the same in the microwave and millimeterwave part of the spectrum as in others: push detector sensitivity to fundamental limits, and make large arrays of detectors.

2 ADVANTAGES & DISADVANTAGES OF COHERENT DETECTORS

Coherent detectors preserve the phase of the incoming signal, as well as its amplitude. They are active devices with gain, unlike passive devices such as bolometers that simply absorb incoming radiation. There are many benefits, but also a cost. There is a noise floor in coherent detectors set by quantum fluctuations. (In the case of a maser amplifier, for instance, this noise floor is simply the spontaneous emission from atoms in a excited state.) In terms of system noise equivalent temperature, this "quantum limit" q can be written as $q = h\nu/(k\log 2) \approx [\nu_{\rm GHz}/20]\,\mathrm{K}$.

The availability of gain in the device defining the noise temperature means, however, that once the quantum tax has been paid, multiple copies of the incident signal can be produced and used without significant increase in noise. These muliple copies may be used in ways that may allow vastly improved control of systematic effects. In principal one can imagine digitizing the raw signal after amplification and performing arbitrary phase and amplitude operations in software with essentially unlimited fidelity. This is a fundamentally different approach from that being pursued with bolometer technology, where the emphasis has been on achieving high sensitivity, controlling the systematics to some degree, and then regressing the remaining level in the data processing step. With coherent techniques, one has the option of designing the system to be largely free of many important systematics at the outset. Examples include: band leveling and band subdivision; modulation of phase; and multiplication of signals (i.e., interferometry).

Amplifiier-based detector systems have practical advantages as well, including: large dynamic range; operation over a broad temperature range, achieving lowest noise at around 20 K; insensitivity to cosmic rays and microphonics; and simplified filtering, taking advantage of their inherent bandpass. These advantages provide a significant reduction in overall system complexity, both in construction and testing/validation, with concommitant decrease in cost.

We discuss these factors in more detail below, starting with noise because it is the factor that has dominated recent discussions about detectors for CMB polarization.

2.1 Noise

The characteristic of bolometers that has lifted them to prominence in the CMB field is the potential for extremely low noise. The linear dependence of quantum noise on frequency guarantees that above some frequency, bolometer systems can achieve lower raw noise than amplifier systems. What is that frequency?

It depends on many factors, both intrinsic to the detectors and as part of the receiver system and its radiation environment. For example, the small dynamic range of bolometers means that actual sensitivity is a strong function of input loading—the same bolometers cannot be used on the ground as in space, because the background radiation level from the atmosphere and ground would saturate space bolometers. And unlike amplifiers, bolometers must be the final element in the detector chain, so any loss of optical efficiency through the optical elements leads directly to a loss of sensitivity.

Figures 1 and 2 compare sensitivities and noise levels for amplifiers and bolometers for ground-based observations (Figure 1) and space (Figure 2). The sensitivities of a "perfect" (i.e., quantum-noise-limited) amplifier and a "perfect" (i.e., photon-noise-limited) bolometer are indicated by black solid and dashed curves, respectively. A 25% bandwidth is assumed for both. The amplifier sensitivity includes a factor of $1/\sqrt{2}$ because amplifiers can measure Q and U simultaneously through a single feed, whereas bolometer or other direct detectors can measure only Q *or* U at one time. The effect of atmospheric loading of the bolometers on sensitivity can be seen by comparing the bolometer curve in the atmospheric windows in Figure 1 with the curve in Figure 2.

In both Figure 1 and 2, sensitivity curves are shown also for amplifiers at 3 and 5 times the quantum limit. Discrete points show measured or projected sensitivity values for various current or planned experiments, as follows:

- BICEP bolometer (from John Kovac), measured
- BICEP2, projected from known bolometer parameters (John Kovac)
- MIC amplifiers, measured
- MMIC amplifier modules for QUIET, measured in lab
- MMIC amplifiers, projected from high frequency, room temperature measurements of 35 nm gate process devices

The horizontal blue and green lines in Figure 1 show the sensitivity required for each of 512 feeds (or planar antennas) at each frequency, to reach 100 nK noise per square degree in the 4% of the sky with the lowest foreground levels, integrating for 1 year (blue) or 4 years (green) from the ground. This is the target noise level recommended by the Task Force on Cosmic Microwave Background Research. Projected amplifiers could reach this level in less than a year up to about 160 GHz. Projected bolometers could reach this level in four years up to same frequency.

With the performance expected from both technologies in the forseeable future, both can reach the recommended noise level in a reasonable experimental lifetime. As will be seen in later sections, the work required to bring amplifiers to the projected level of performance will take several years. But if an instrument with $3 \times q$ amplifiiers can be deployed in 2012, and if the performance expected of bolometers is realized on the projected schedule, then *by 2013, both bolometer and HEMT experiments could reach 100 nK deg*^{2} *over the cleanest 4% of the sky*. This would result in:

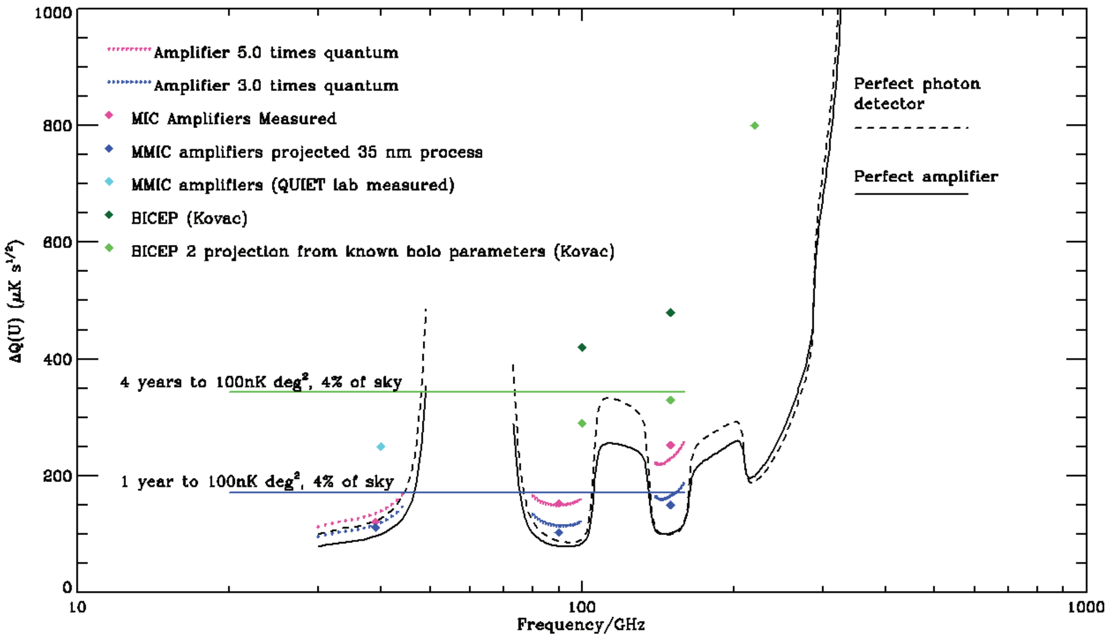

FIG 1.—Sensitivity of a quantum-limited amplifier compared with the sensitivity of a photon-noise-limited bolometer (i.e., "perfect" amplifier and bolometer, respectively), from the ground at a high, dry, site. The dramatic effect of the atmospheric loading on bolometer sensitivity even in the good atmospheric windows can be seen by comparison with Figure 2. We assume 8 K of thermal noise from the telescope and ground, independent of frequency—surely is an overestimate at low frequencies—and a 25% bandwidth for both detector systems. The amplifier sensitivities are divided by $\sqrt{2}$ because an amplifier polarimeter can measure Q and U simultaneously, while a bolometer measures Q or U at a given time. For a description of the various colored points and lines, see text.

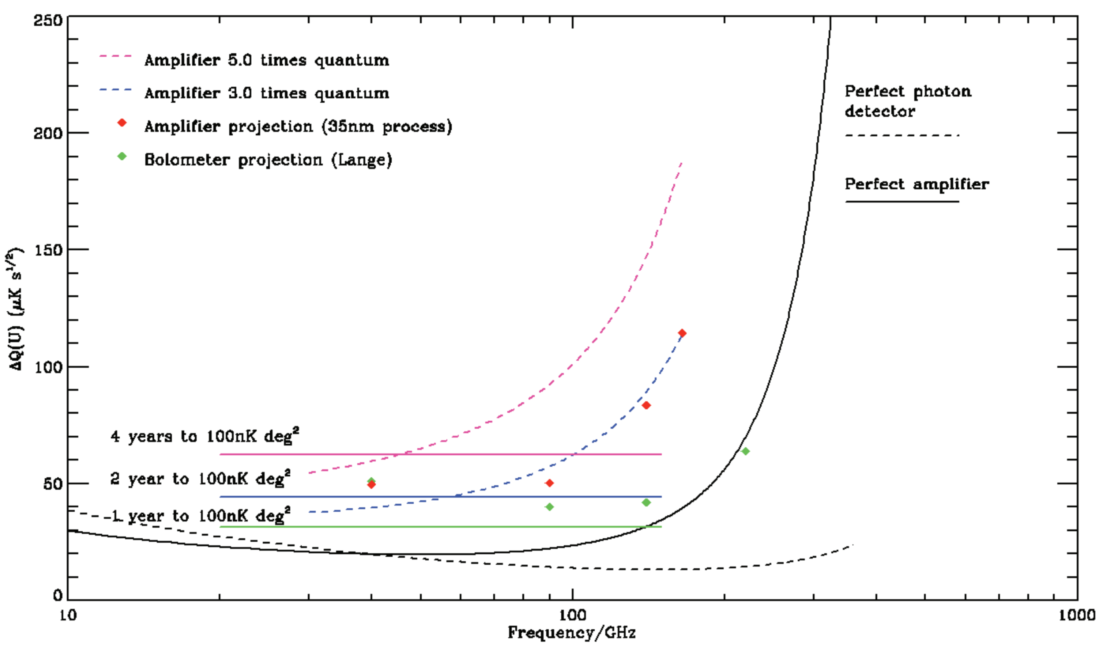

FIG 2.—Sensitivity of a quantum-limited amplifier compared with the sensitivity of a photon-noise-limited bolometer (i.e., "perfect" amplifier and bolometer, respectively), in space. Below 40 GHz photon noise would dominate quantum noise for the amplifier. We have not added the two together so that their relative strength can be seen. The amplifier sensitivities are divided by $\sqrt{2}$ because an amplifier polarimeter can measure Q and U simultaneously, while a bolometer measures Q or U at a given time. For a description of the various colored points and lines, see text.

- Possibly a hint of more of B-modes
- Certainly a great deal of essential information on foregrounds
- An assessment of systematics for two different detection systems, assess in a real and stressful environment.

We believe that we should work towards this situation, and that a down-select between the two technologies should not take place before this comparison can be made.

In Figure 2, discrete points show:

- MMIC amplifiers, projected from high frequency, room temperature measurements of 35 nm gate process devices
- Bolometers, projected (Andrew Lange)

The horizontal green, blue, and magenta lines in Figure 2 show the sensitivity required for each of 256 feeds (or planar antennas) at each frequency, to reach 100 nK noise per square degree over the full sky, integrating for 1 year (green), 2 years (blue), and 4 years (magenta) in space. Projected bolometers could reach this level in 2 years up to about 140 GHz, and in 4 years up to about 220 GHz. Amplifiers could reach this level up to about 140 GHz in 6 years.

2.2 Foregrounds & Frequency range

For CMB polarization. foregrounds are a critical consideration, and may well be the limiting factor in measuring B modes. The June workshop has considered foregrounds at length. Figure 3 shows foreground levels compared to CMB fluctuations for various sky areas, from full sky to the quietest (i.e., lowest foreground fluctuation) 23% of the sky, as calculated from angular power spectra of the various components based on the Planck Sky Model (see June workshop). Although limited regions of the sky have much smaller fluctuations, the lowest multipoles require as close to full-sky observations as possible. And since the lowest multipoles are where the reionization bump makes the B-modes the strongest compared to other sky signals, they are the prime target for a space CMB polarization mission.

Simulations of component separation by Dickinson et al. (reported at the June workshop) suggest that experiments with SNR independent of frequency will give the best results (i.e., lowest error on the CMB itself for a given focal plane detector area). The signal of relevance is the *total* signal, CMB+foregrounds, not the CMB alone. If this preliminary result holds up, it is clear from Figure 3 that experimental noise can and should be much higher at low and high frequencies than near the foreground minimum. *Neither a large number of detectors achieving low noise at high frequencies nor a large number of (large) detectors dominating the focal plane at low frequencies would be useful.*

If frequencies much higher than 150 GHz are required, amplifiers will not be the detector of choice because of their raw sensitivity disadvantage compared to bolometers. If frequencies up to about 150 GHz are enough, however, an amplifier mission will be very attractive.

2.3 Advantages

2.3.1 Signal processing and design possibilities

From a systems perspective coherent receiver technologies have many attractive features for precision polarimetry. In particular, the availability of gain in the device defining the noise temperature allows multiple copies of the incident signal to be produced and used to measure the properties of multiple incident radiation modes. This ability opens up a variety of signal processing and instrumentation approaches, many developed for radio, radar, and radioastronomy. These techniques share a common element. By appropriately modulating the desired signal (e.g., polarization state,

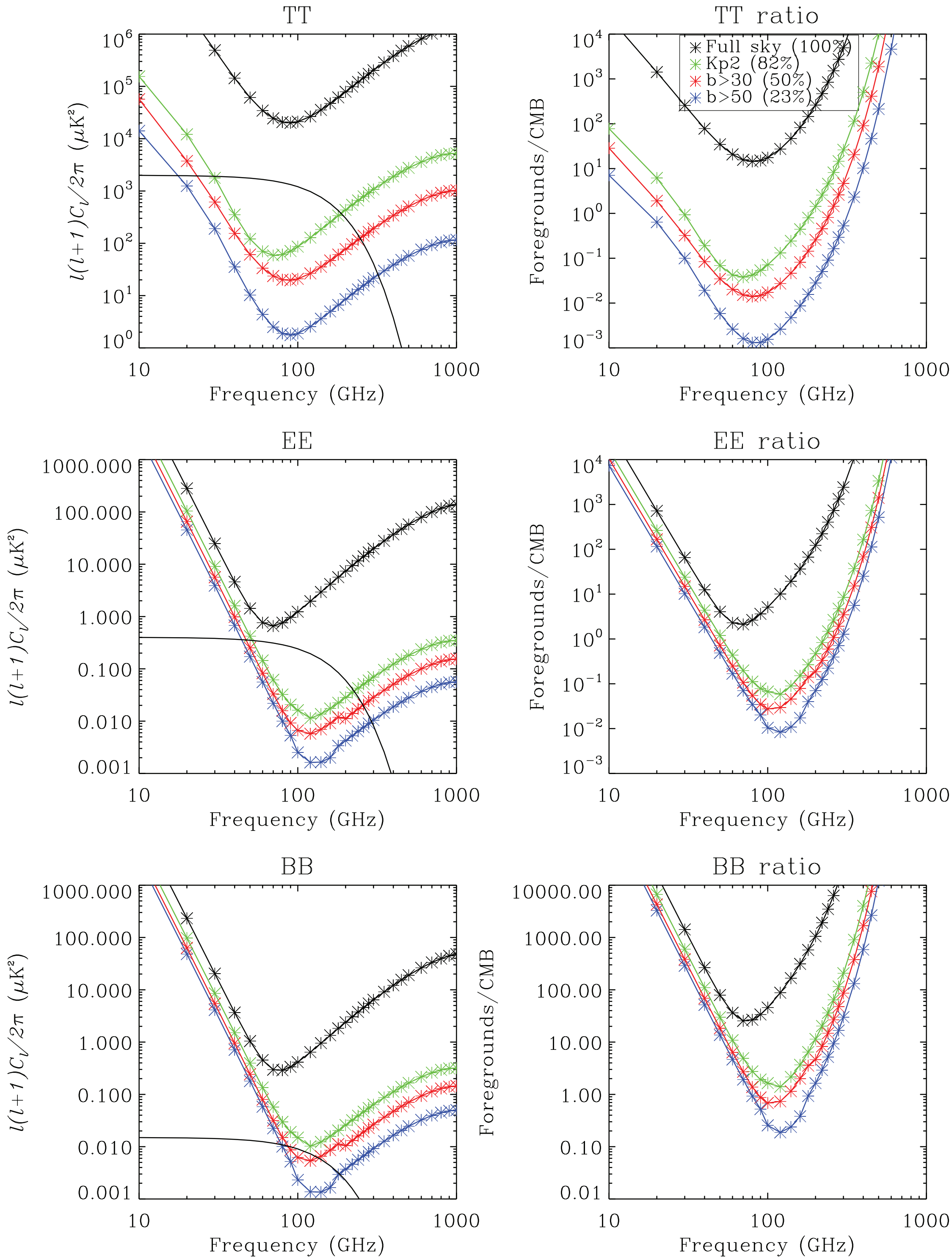

Fig 3.—Level of synchrotron and dust temperature fluctuations in absolute units (*left*) and relative to the CMB (*right*), calculated over different regions of the sky (i.e., different Galactic "cuts") as indicated in the upper right panel. The lowest multipoles can be observed only from space, and only by observing a large fraction of the sky. The lower curves representing small sky fractions are therefore relevant only for suborbital experiments. The foregrounds are based on the Planck Sky Model (see Theory and Foregrounds workshop for details). Too little is known about polarized foregrounds to support conclusive simulations, but there is no question that at high and low frequencies foreground fluctuations will dominate the measured signal. For example, in TT for a Kp2 sky cut, for which the foregrounds are known moderately well from WMAP up to 94 GHz, at 40 and 130 GHz dust and synchrotron fluctuations are up by a factor of five over their values at the minimum at 70 GHz. At 30 and 180 GHz the foregrounds are up by a factor of 25. By 300 GHz, dust fluctuations are up by three orders of magnitude compared to CMB fluctuations, which drop fast on the Wien side of the spectrum. If the foreground spectra are complicated, a very wide frequency range may be disadvantageous. [Figure from Clive Dickinson.] For EE the foreground data are much more uncertain, especially concerning dust, for which there is suspicion that the Planck Sky Model underestimates polarization fluctuations. From Figure 3, however, the green curve in the EE ratio plot reaches the same values at about 50 and 240 GHz.

incident angle, intensity, frequency, phase) and sampling the data, the system is able to suppress strongly undesired and competing signals that may be present in the instrument's environment.

These techniques are possible in a coherent receiver because the fields and phase are preserved by the receiver. As a result, the signal can be appropriately processed by subsequent circuitry (e.g., polarization diplexers, quadrature hybrids, magic-tees, in phase power splitters, phase delay/modulator) as necessitated by the desired system requirements before power detection. This ability to encode the desired properties of the optical signal's fields and subsequently look for correlations is a powerful tool for obtaining precision control over systematic effects. More importantly, in a single-mode coherent system, each incident mode (i.e., in our case of interest polarization state) can be independently processed. In practice, examples from precision radiometry (Predmore et al. 1985), interferometry (Blum 1959; Faris et al. 1967), and polarimetry (Tinbergen 1996) have demonstrated the power and maturity of this overall approach. Incoherent systems do not have this option, and typically rely upon synchronous modulation/demodulation of the incident power or interferometer approaches in front of the detection. In the absence of detector gain, this can place severe system constraints upon the allowable loss, emission, physical temperature/stability, as well as achievable switching speeds. Stated another way, coherent receivers are able to make an essentially real time vector measurement while incoherent systems make a scalar determination of power.

The advantages afforded by preserving the signal phase in a coherent receiver come at the cost of quantum noise, which grows linearly with frequency. Nevertheless, what is gained by preserving phase should not be understated:

- Such a coherent system will have relatively modest cooling requirements (i.e., 20 K) compared its cryogenic counter part (i.e., 0.1 K);
- Depending upon the details of the channel selection, similar noise can be achieved with potentially higher overall stability and potentially greater detector speed; and
- Costs will be lower for pre-launch system validation. This is a significant consideration.

In § 2.3 we discuss the crossover in noise properties of HEMT-based coherent polarimeters and incoherent detectors. The polarization properties of astronomical foregrounds will ultimately determine the number and frequency ranges required, and the weight to be given to the various considerations outlined above. As such, the potential advantages of these signal processing techniques should considered seriously in deciding how to best obtain the desired polarimetery data.

Ultimately one will need to understand the data from a large number of the polarmetric channels in the presence of real world flight environment—thermal drifts, finite beams and sidelobes, differing frequency responses, astrophysical foregrounds, and other forms of radiation. In considering these challenges, merely encoding/decoding the incident signals is not sufficient. Calibration of the system response will require instrument stability on a time scale long compared to the modulation in order to achieve the ultimate detector sensitivity. The resultant linkages between detector speed/noise, scan, modulation, and calibration rates required to achieve the mission goals can be addressed in either system approach; however, when considering a system's overall testability and the ability to minimize/retire risk before flight, a coherent system has strong advantages.

At millimeter wavelengths the realization of ideal-correlators (multipliers) with a broad-band response presently presents technical challenges (Predmore et al. 1985). For this reason pseudo-correlation approaches have found use for CMB applications (i.e., WMAP, Planck LFI, QUIET, etc.). In the table below examples of phase switched pseudo-correlation signal detection schemes are summarized. (note: A Jones matrix formulism was used to compute the response of a selection of polarization sensitive receiver topologies. See Jones 1941, 1942.) In selecting such a receiver configuration for polarimetry it is important to know how the residuals and baseline (i.e., the portion of the signals which ideally would not be present) should be considered in addition to desired lock-in channel sensitivity.

TABLE 1

Phase-Switched Pseudo-correlation Signal Detection Schemes

Example	Measurement Approach	Sensitivity/Residual (Baseline)
1	$J_{180H} J_{\Delta\phi} J_G J_{OMT} \vert E_{\rm in}\rangle$	$\pm U/V(I$ and $Q)$
2	$J_{180H} J_{\Delta\phi} J_G J_{90H} J_{OMT}$ $J_{180H} J_{\Delta\phi} J_G J_{CPH} \vert E_{\rm in}\rangle$ $J_{180H} J_{\Delta\phi} J_G J_{OMT} J_{QWP}(\pi/4) \vert E_{\rm in}\rangle$	$\pm U/Q(I$ and $V)$
3	$J_{180H} J_{\Delta\phi} J_G J_{180H} J_{OMT} \vert E_{\rm in}\rangle$	$\pm Q/V(I$ and $U)$
4	$J_{180H} J_{\Delta\phi} J_G J_{180H} J_{OMT}(0) \vert E_{\rm in}\rangle$	$\pm V/U(I$ and $Q)$
5	$J_{90H} J_{\Delta\phi} J_G J_{OMT} \vert E_{\rm in}\rangle$	$\pm V/U(I$ and Q
6	$J_{90H} J_{\Delta\phi} J_G J_{OMT} \vert E_{\rm in}\rangle$ $J_{90H} J_{\Delta\phi} J_G J_{CPM} \vert E_{\rm in}\rangle$ $J_{90H} J_{\Delta\phi} J_G J_{OMT} J_{QWP}(\pi/4) \vert E_{\rm in}\rangle$	$\pm Q/U(I$ and V
7	$J_{90H} J_{\Delta\phi} J_G J_{180H} J_{OMT} \vert E_{\rm in}\rangle$	$\pm V/Q(I$ and $U)$
8	$J_{90H} J_{\Delta\phi} J_G J_{OMT} J_{QWP}(0(\vert E_{\rm in}\rangle$	$\pm U/V(I$ and $Q)$

2.3.2 Dynamic range

Amplifiers can handle a very large range of input signal levels. Non-linearities are much less than seen for bolometers. Even more importantly, the noise temperature depends very little on input signal level up to very high levels. The rapid degradation of bolometer performance with photon load, which requires bolometers to be built differently for ground and space applications, and even for different telescope temperatures, is not an issue with amplifiers.

2.3.3 Operating temperature and testability

Amplifiers work over a broad temperature range, from above room temperature to well below 4 K. The noise of the current generation of HEMTs decreases by roughly an order of magnitude from room temperature to 20 K, below which there is little effect. This has broad impact on system design:

- Thermal and cooler systems to achieve 20 K are substantially simpler than systems to achieve sub-kelvin temperatures.
- There is the possibility of achieving very good (although not optimum) noise performance with passive radiative cooling only. The power that can be dissipated by a given radiating area goes as T^4. It is difficult to distribute the concentrated heat dissipated by an amplifier focal plane uniformly over a large radiating area, and even to the extent that that can be done, the radiating area required would become quite large at 20 K or so, the optimum temperature of operation. However, with a fourth power dependence, a temperature of 40 K or so is much easier to achieve.
- An amplifier system designed to operate cryogenically (say 20 K) can be checked out and tested very well at higher temperatures. Both for ground testing and for in-orbit checkout this can result in substantial simplifications and savings.

2.3.4 Insensitivity to cosmic rays and microphonics

Cosmic rays produce no detectable disturbance in the output signal of amplifiers. Although "spider web" type bolometers have reduced the susceptibility of bolometers to cosmic rays dramatically, detection and removal of cosmic rays spikes is still a first and necessary step in the processing of bolometer data from Planck. Up to a few percent of Planck HFI data will be thrown away because of this.

2.3.5 Filtering

As an added benefit, the presence of in-band gain lowers the overall filtering requirements to limit the influence of out band response.

2.3.6 Complexity and arrayability

As shown below in § 3.2, cost-effective techniques for building large arrays of amplifier detectors have been demonstrated. Signals can be digitized at the cryogenic stage, eliminating the need for complicated cryogenic readout/multiplexer circuits.

2.3.7 Industrial infrastructure

Amplifiers are the detector of choice for communications and remote sensing applications in the commercial and military world up to frequencies of several hundred gigahertz, at least. Moreover, while optimization of amplifiers for cryogenic operation may well be different from optimization at room temperature, it is a general rule that the best devices (transistors, MMICs) at room temperature will be the best devices at cryogenic temperatures. As a result, the commercial and military development of high performance amplifier systems is of direct benefit to the scientific world. The area of low noise amplifier technology is a technology that NASA does not have to develop on its own. Significant synergies exist. This substantially decreases the size of the investment in technology required to realize the best cryogenic performance.

2.4 Disadvantages

2.4.1 Quantum noise

As described in § 2, there is a lower limit to $T_{\rm sys}$ for coherent receivers set by quantum fluctuations. But as shown in § 2.1, even with quantum noise amplifiers can reach the noise levels required for CMB polarizaiton over a broad frequency range.

2.4.2 Power dissipation

Amplifiers dissipate significant power. A W-band (75–110 GHz) module to measure Q and U simultaneously with present technology dissipates about 12 mW, from which predictions at other frequencies can be made: 4 mW and 30 GHz, 7 mW at 40 GHz, 10 mW at 70 GHz, and 15 mW at 150 GHz. Hundreds of detectors would require watts of heat lift at 20 K or so. A cooler with this kind of heat lift would have a major impact on flight system design, but is not a showstopper by any means. For example, the two hydrogen sorption coolers on Planck were combined together into a single cooler, with a JT valve optimized for a 45 K radiative precool temperature, would have a heat lift of about 4 W with 1100 W of input power. If a radiative precool temperature of 35 K could be achieved, the heat lift for the same power input would be 10 W. This is serious but not scary power in space.

2.5 Summary of Operational and Systematic Comparisons

Table 2 summarizes the characteristics and practicalities of amplifier detectors, with comparison to bolometer systems.

TABLE 2

Operational and Systematic Comparison of HEMT and Bolometer Arrays

Requirement	MMIC HEMTs	Bolometers
Response time	Excellent, $\tau \approx 1/\beta$	Adequate, can be modeled
Linearity	Excellent	Adequate, can be modeled.
Dynamic range	Large	Small. Different devices required for space and ground.
Gain stability	Excellent with modulation	Excellent for Planck (NTD Ge technology), not yet public for TES
Offset stability	Excellent with modulation	Excellent for Planck (NTD Ge technology), not yet public for TES
Polarization systematics	Excellent, Q and U from same pixel. Modulation electronic and fast, after amplification. Effect of gain mismatch removed by radiometer design.	Good, Q and U from different pixels, or complicated and relatively slow modulation. Gain mismatch leads to leakage of temperature to polarization.
B-field, microphonics, EMI, RFI susceptibility, cosmic rays	Good	Adequate (?). B-fields a particular issue for TES.
Device uniformity	Not established	Good for Planck, not yet public for TES
	Practicalities for Space	
Cooling requirements	Passive + active (20 K). Heat lift requirement large but achievable. Passive + passive (40 K) with some loss of sensitivity.	0.1 K operation requires multi-stage cooling chain. Loading per detector depends on parasitics. Complicated.
System testability & risk reduction before flight	Easier & less expensive	Harder & more expensive
Cryogenic readout & multiplexer	Not needed	Complicated

3 TECHNOLOGY STATUS AND PROSPECTS

Dramatic improvements in noise and power dissipation of transistors have been achieved over the last 20 years, first with high electron mobility transistors (HEMTs) fabricated on GaAs substrates, then on InP substrates. Developments over the last two years promise noise performance of a few times the quantum limit in the forseeable future over a large frequency range.

Similarly dramatic advances have been made over the last few years in the packaging of amplifier receivers, making large arrays of receivers possible and achievable for CMB polarization. We discuss the state of both areas below, and identify technology development required to realize the kind of performance required for B-mode measurements on the ground or in space.

3.1 Transistor and Amplifier Performance

Figures 4 and 5 show the state of the art for cryogenic performance of transistor amplifiers in 2007. In 2006, Northrop Grumman Corporation (NGC) developed a new ultra-short-gate-length high electron mobility transistor (HEMT) process* (Deal et al. 2006), incorporating the following changes:

* Funded in part by the DARPA Submillimeter Wave Imaging Focal-plane Technology (SWIFT) program, whose goal is room-temperature imaging arrays at submillimeter frequencies.

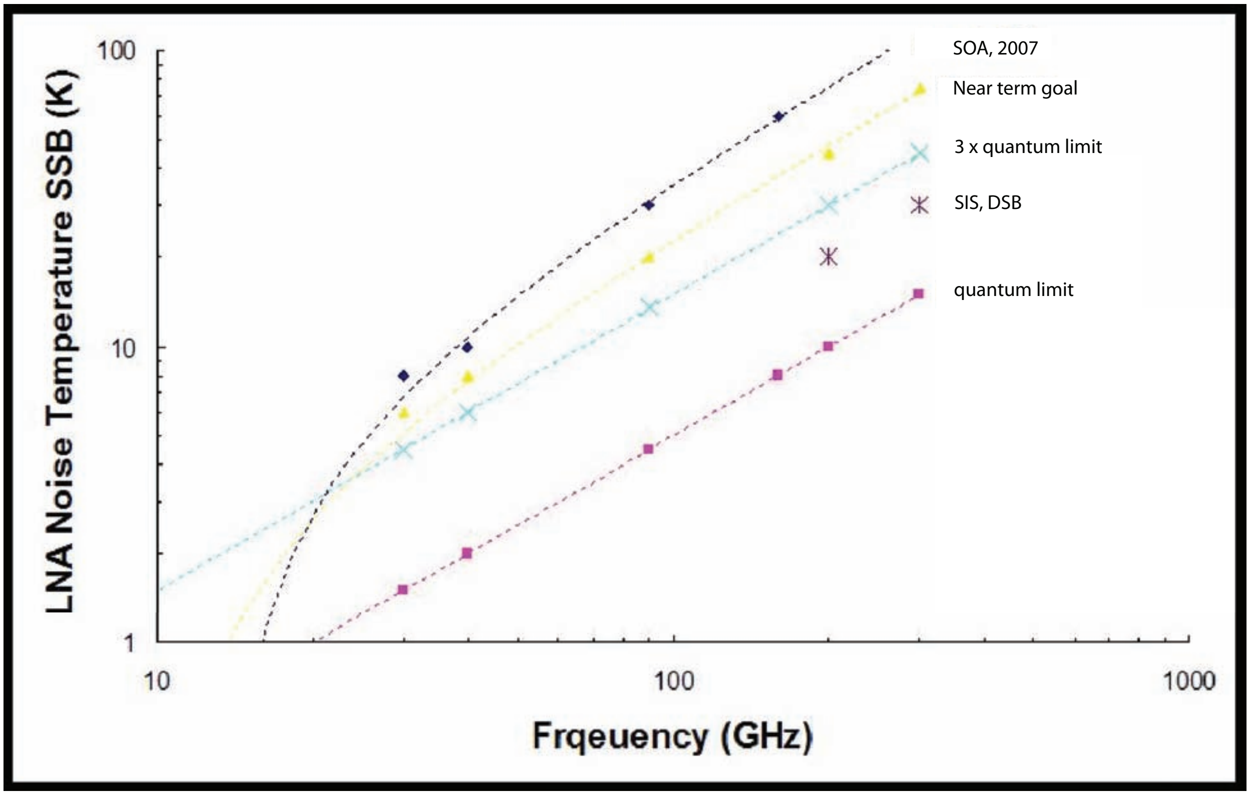

Fig 4.—Amplifier noise temperature vs. frequency for the state-of-the-art in cryogenic noise performance in 2007, as well as 3 and 10 year goals. Double sideband SIS mixers are shown for comparison. Single sideband SIS mixers would have twice the temperature, approximately the same as the 10-year goal for amplifiers.

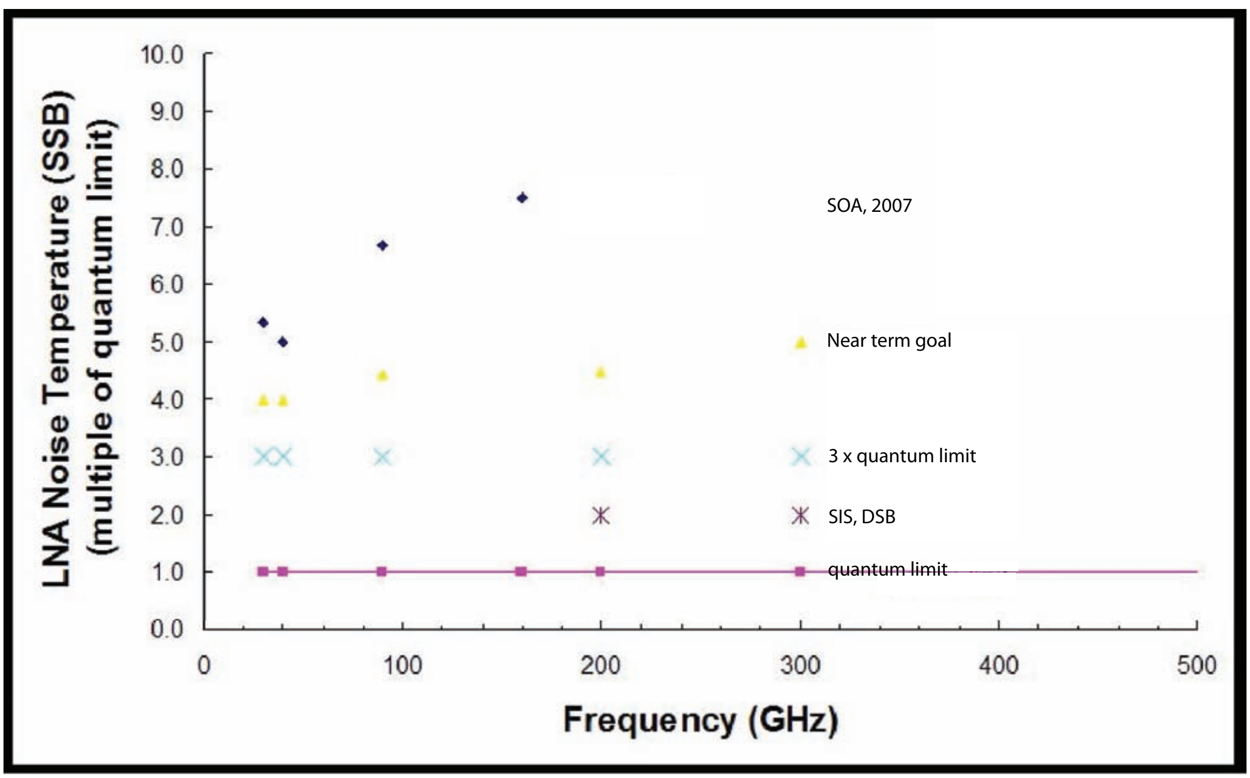

Fig 5.—Same as Figure 4, but as a multiple of the quantum limit.

- gate length reduced from 0.1 μm to 0.035 μm $\Rightarrow$ parasitic gate-source capacitance is reduced and cutoff frequency is increased by a factor of 2
- ohmic metal and contact resistance reduced by a factor of 2
- InAs channel enabled through new epitaxy design $\Rightarrow$ improved electron mobility by 25%
- 2-mil thick wafer process $\Rightarrow$ reduction of via hole size and pads by as much as a factor of 4, to support higher frequency designs
- reduction of minimum line size and spacings by 30-40%

The results from this new process have been spectacular. The first high gain submillimeter-wave amplifiers have been produced, setting a new benchmark for the highest frequency amplifer at 340 GHz (up from 225 GHz)—limited by the test set, not the amplifier itself (see Fig. 4). Gain at 200 GHz is 5 dB more per stage than the previous best.

Most of the work to date on devices from this process has been at room temperature and at frequencies near 300 GHz. Some results are given below.

A transistor model based on measurements on-wafer predicts that the 35 nm devices have a maximum stable gain (MaxGain) of 5 dB up to 600 GHz (Fig. 6), with 10–17 dB gain per stage predicted from 30–200 GHz, under ideal circuit matching conditions.

Fig 6.—Predicted maximum available/maximum stable gain (MaxGain) of the 35 nm gate HEMTs. MaxGain is above 5 dB up to 600 GHz, and is between 10 and 17 dB for frequencies between 30 and 200 GHz.

Amplifiers using this technology that give breakthrough performance up to 340 GHz at room temperature have been reported by Dawson et al. (2005), Deal et al. (2006, 2007), Gaier et al. (2007), Pukala et al. (2008), Samoska et al. (2008), and Kangaslahti et al. 2008). Figure 7 shows a 3-stage amplifier with 15 dB of gain at room temperature, or 5 dB per stage. This design is the highest frequency amplifier reported to date, and shows excellent correspondence between modelled and measured results (Fig. 8).

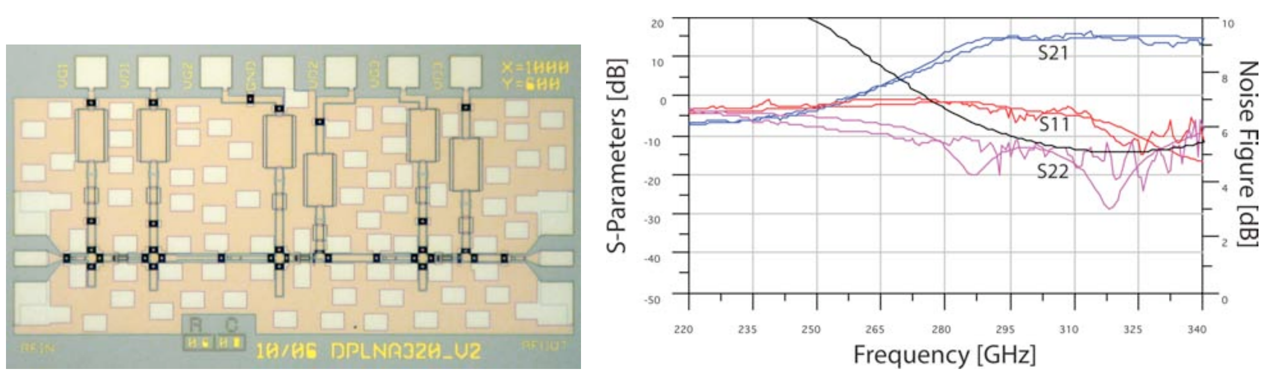

Fig 7.—*Left*—Three-stage MMIC amplifier with 15 dB of gain from 285–340 GHz at room temperature. *Right*—Three-stage MMIC amplifier measurements and model of S21 (gain), S11 (input return loss), and S22 (output return loss). In each case, the smoother curve of the pair shows the model. Excellent agreement is seen between the measurements and the model. The black curve shows modelled noise figure (right-hand scale, see § 2.2.2). The high frequency is limited by the frequency range of the measurement, not of the amplifier.

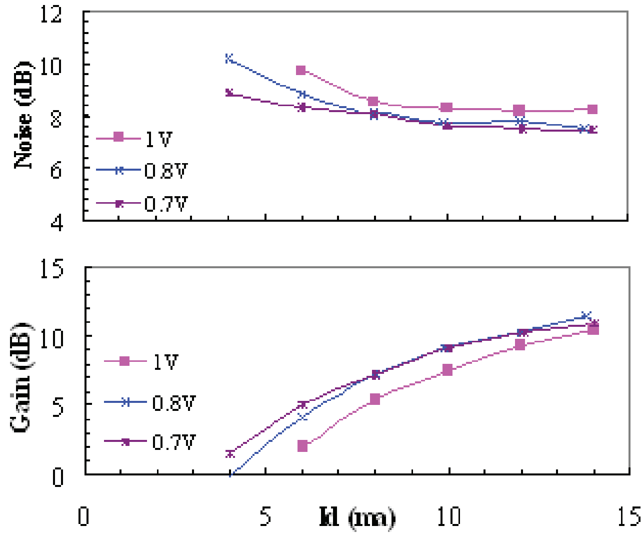

FIG 8.—Measured noise figure and gain for a 270 GHz amplifier at room temperature. $NF = 7.5\,\mathrm{dB}$ at maximum gain of 11.5 dB.

The technology has demonstrated very low noise at these frequencies (Deal et al. 2006; Gaier et al. 2007), with noise figure† of 7.5 dB at room temperature for a 270 GHz LNA (Fig. 5).

3.1.1 Cryogenic Performance

The lowest noise is achieved with amplifiers cooled to cryogenic temperatures. Little change in noise has been observed below 20 K physical temperature, so hereafter "cryogenic" will mean ~ 20 K unless otherwise specified. Kangaslahti et al. (2008) characterized the noise performance of a three-stage MMIC amplifier for the 180 GHz band as a function of physical temperature (Fig. 9). At room temperature, the noise temperature at 160 GHz is less than 400 K, a factor of two smaller than the previous state of the art, with gain of $\sim$16 dB. At 30 K physical temperature, the noise temperature is < 100 K up to 170 GHz, the lowest cryogenic LNA noise temperature ever reported at these frequencies. These improved cryogenic results were obtained even though the amplifier showed a clear "kink effect" in its cryogenic DC I-V curves. This precluded proper biasing of the amplifier, increasing its noise.

In general, the noise of InP transistors (whether MIC of MMIC) has decreased by roughly an order of magnitude from room temperature to 20 K. The factor of four measured for the 180 GHz amplifier is clearly less than a factor of 10, even allowing for the small additional reduction that would be expected between 30 K and 20 K physical temperature. One might worry that cryogenic performance is being limited in the 35 nm gate devices by some factor not previously seen in other devices. An even more recent measurement shows that this is not the case.

Figure 10 shows the noise temperature for a W-band amplifier built by Eric Bryerton at NRAO cooled to about 15 K. From 300 K to 15 K the noise decreased by a factor of ten.

3.1.2 Noise Models and Predictions

The key question is how close to the fundamental quantum limit can amplifiers be brought, and what is required to get there? A more immediate question is what is the full cryogenic potential of the 35 nm gate devices now being produced? Their performance greatly exceeds anything seen

† *Noise figure* in dB is the standard measure of noise in the non-astronomical world. The correspondance between NF and noise temperature T, the astronomical standard, is given by $NF = 10 \log\{T/290 + 1\}$, with T in kelvin.

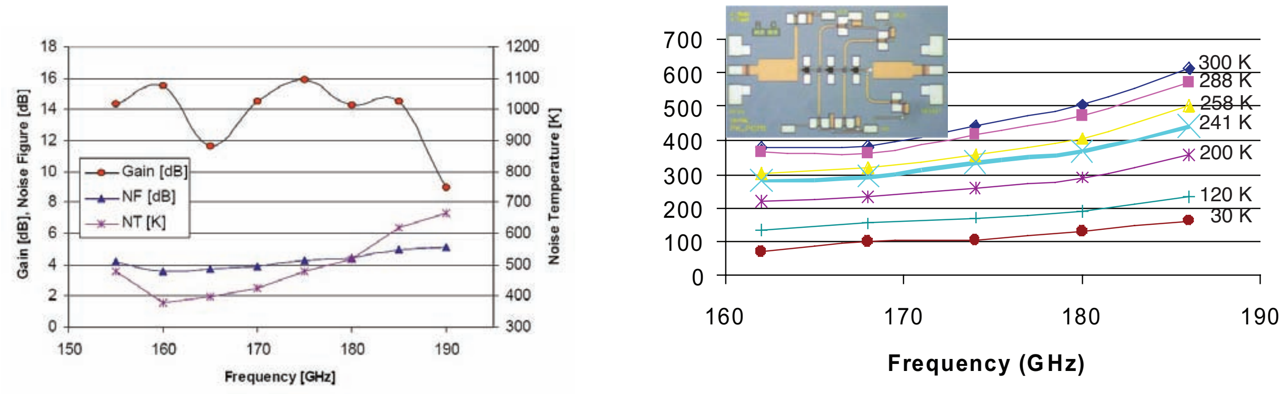

FIG 9.—Measurements of 180 GHz amplifier (inset photo) at room temperature (*left*) and as a function of temperature down to 30 K (*right*). Noise is a factor of two lower than the best previous results at both room and cryogenic temperatures. The low cryogenic noise was obtained despite the fact that the DC bias performance was not optimum (a clear "kink effect" was seen in the cryogenic I-V curves; see § 2.2.3).

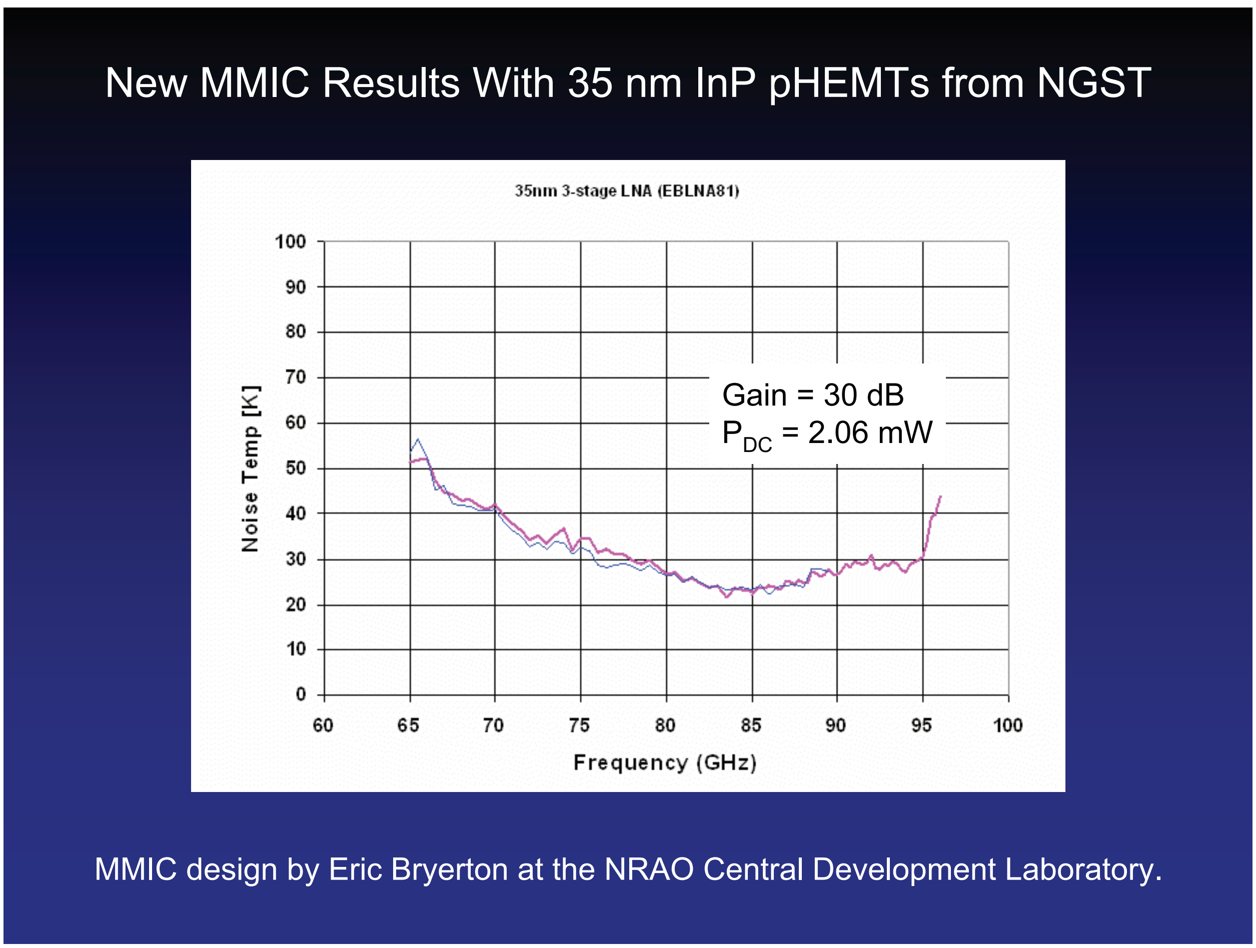

FIG 10.—W-band MMIC amplifier cooled to $\sim$ 15 K. The noise is the lowest ever measured for an amplifier at these frequencies, and an order of magnitude lower than at room temperature

before, judged by room temperature performance at frequencies up to ~350 GHz and the first cryogenic measurements. Even more specifically, we can ask what gains in performance can be realized at cryogenic temperatures over the range of frequencies important for CMB polarization?

A theoretical answer to the second question can be given by a noise model of the new devices. For nearly two decades, the standard model of low noise transistor noise has been that of Pospieszalski (1989), which uses two noise sources, one on the gate and one at the drain of the device. These noise sources are realized in practice by setting the physical temperatures of the R_g and R_{ds} to values that match our measured results. The correct temperature of the R_g is the physical temperature of the circuit (either 295 K or 20 K, depending on whether we model the room temperature or cryogenic performance of the amplifier). The r_{ds} models the drain noise of the transistor and is typically 15–20 times the physical temperature of the device, depending on the technology. Kangaslahti (private communication) has developed such a model, and with it obtains a noise figure of 3.3 dB for a single device at 270 GHz. If cascaded in a three stage amplifier with 11.5 dB of gain (assuming 1.5 dB losses in passives in each stage), this would translate to a noise figure of 6.7 dB for the amplifier in Figure 5, in good agreement with the measured value of 7.5 dB.

Using this noise model at 20 K gives the results shown in Figure 11. The simulated noise temperature is 7.9 K ($4q$) at 40 GHz, 11.5 K ($2.6q$) at 90 GHz, 19.5 K ($2.8q$) at 140 GHz, and 24 K at 165 GHz. All designs had more than 20 dB of gain, so these numbers would be very close to the final noise temperature of the actual receiver (i.e., later components in the receiver signal path would have little effect on the system noise). These design simulations are preliminary and not optimized. And although the predicted performance is still a factor of two better than measured for the amplifier in Figure 10 that was the very first W-band 35 nm amplifier measure cryogenically.

All of this suggests that **there is an excellent prospect of achieving noise levels of $\sim 2.5q$ over a range of frequencies important for CMB polarization, levels which only a year or two ago seemed far off in the future.** Figures 1 and 2 show that these levels would enable CMB polarization experiments and missions with the capabilities recommended by the TFCR.

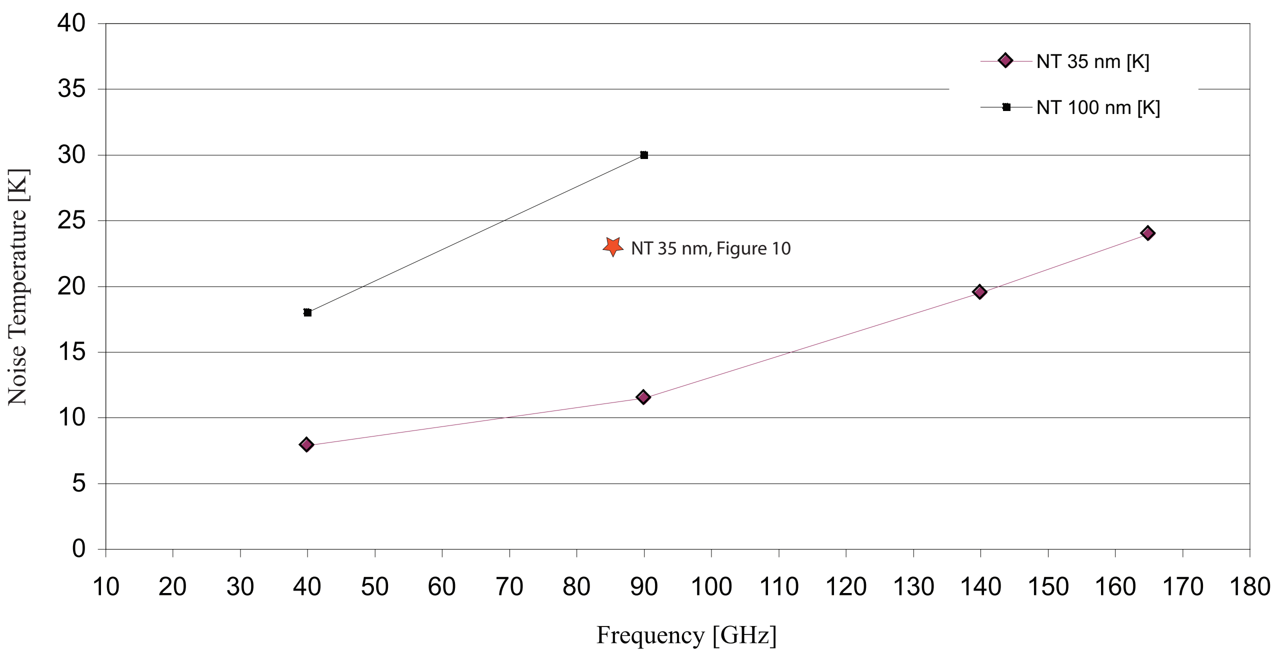

Fig 11.—Noise temperatures for the 35 nm devices predicted at 40, 90, 140, and 170 GHz by the noise model extrapolating to lower frequencies and **cryogenic temperatures**. The improvement predicted over the best previous transistors (upper line in the plot) is dramatic.

3.2 Arrays and array performance

The experimental sensitivity needed for B-mode observations requires both low noise from individual detectors and many detectors. The detectors used for WMAP and Planck, whether amplifiers or bolometers, could not be scaled up to a level of hundreds of detectors per frequency. Over the last few years, designs for highly scalable coherent radiometers and polarimeters have been demonstrated and implemented in the QUIET experiment. The following figures are from QUIET.

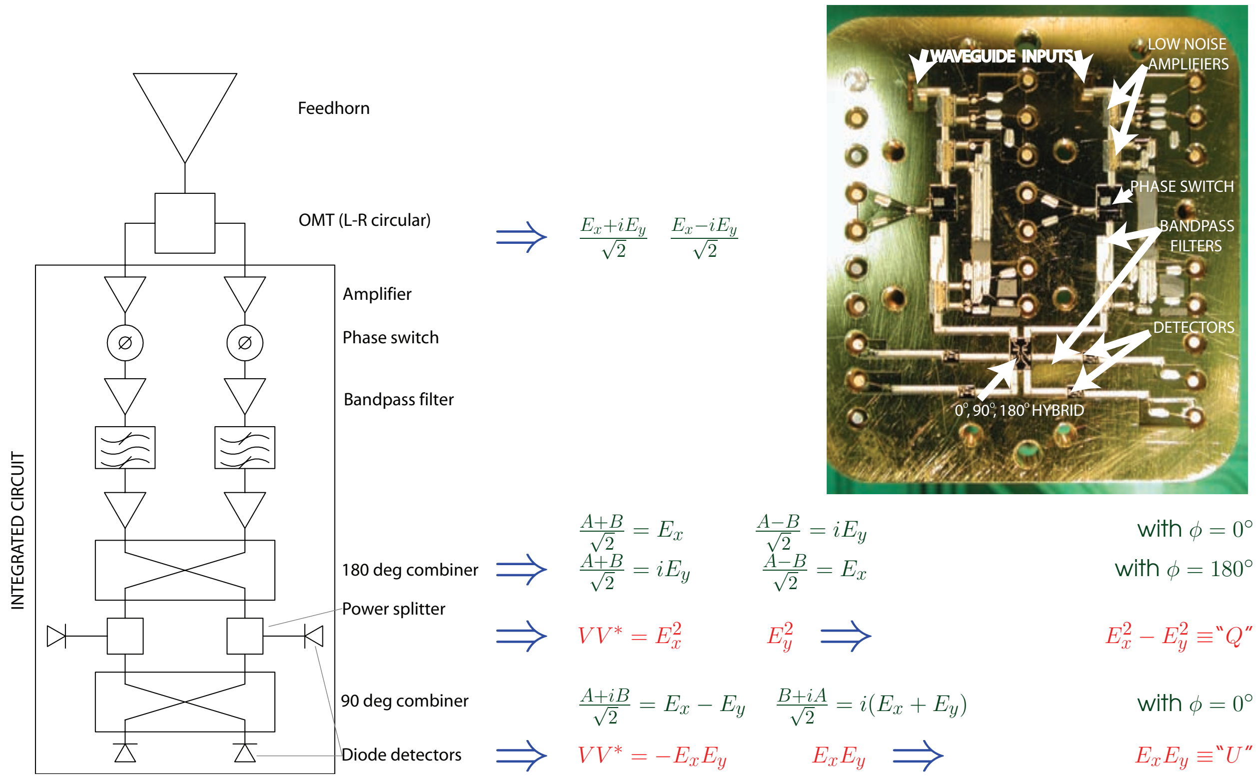

FIG 12.—Schematic and photograph of a QUIET W-band polarimeter module, showing how Q and U are measured simultaneously through each feedhorn. The module, which contains all radiometer components following the OMT up to and including detectors, is about $1\rlap{.}''25 \times 1''$ in size, and fits into a standard circuit board socket, which supplies bias voltages and output signals. The modules are cooled to 20 K; bias supplies and signal processing electronics operate at room temperature. The modules can be assembled by machine, and can be built up into very large arrays.

Three key points can be made about large arrays of coherent polarimieters suitable for B-mode instruments:

- The basic packaging technology for large arrays has been demonstrated. No technological breakthroughs, such as the development of cryogenic multiplexers for large bolometer arrays, are required. This is another manifestation of the simplicity of coherent systems that results from being able to transform the incoming signal into more convenient form without loss of information, once the quantum tax is paid. Savings in fabrication, assembly, integration, and testing of roughly two orders of magnitude over discrete component techniques used in the past are in hand. These techniques seem appropriate for arrays of the size that can be fit into the undistorted focal plane areas of CMB telescopes.
- Even more highly integrated packaging techniques, using multiple wafers stacked in 3-D, are being developed, and could be used for even larger arrays if there were a need. Set-up costs would be higher, but per unit costs could be much lower for large numbers.

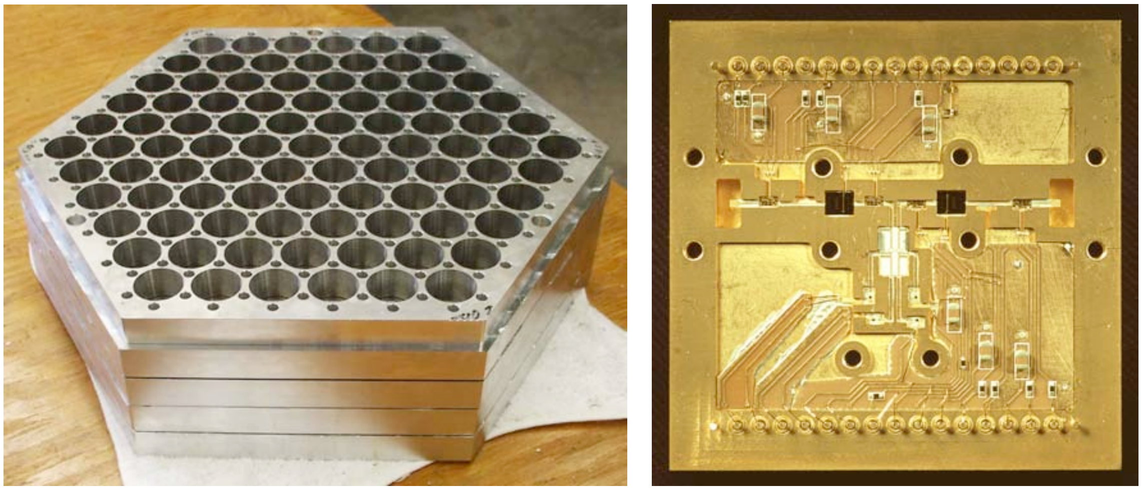

FIG 13.—*Left*—QUIET W-band 91-element feed array. This is a "platelet" array, in which an array of corrugated feed horns is built from many layers of aluminum with appropriately sized holes machined in them, all vacuum welded together. [Josh Gunderson, Miami] *Right*—QUIET Q-band module. Larger than the W-band module in Figure 13 because the array spacing for this wavelength is greater, the Q-band module combines some of the discrete components of the W-band module onto miniature circuit boards, making automated assembly even easier.

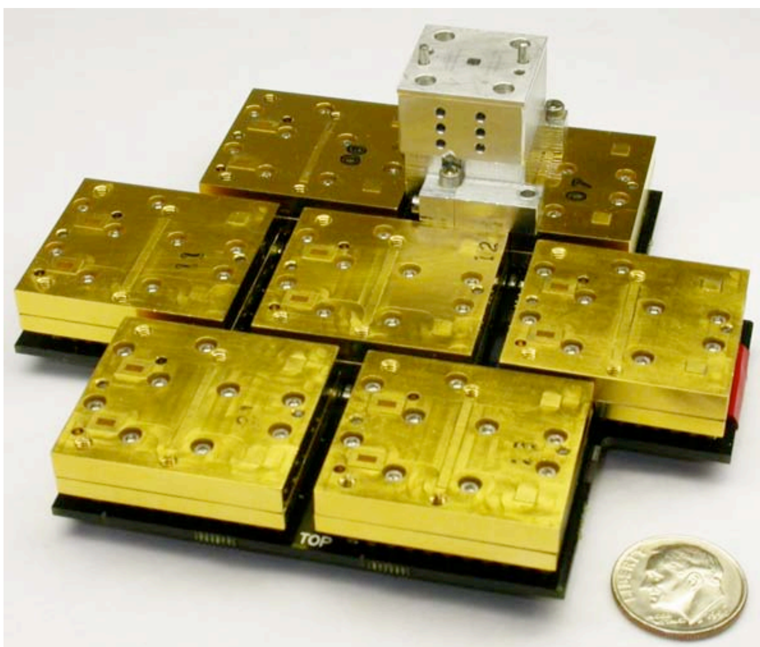

FIG 14.—Test array of seven W-band modules mounted in standard sockets on a circuit board. One left-right circularly polarizing orthomode transducer (OMT) is attached to one module at the top. It is straightforward to build up large hex-packed arrays from these basic components. [Chicago]

- Although the basic arraying techniques have been well-demonstrated, there is one critical area in which current results are inadequate. In going from MMIC to module, a performance hit of a factor of roughly two is suffered. That is, the noise temperature of the module is roughly twice the noise temperature of the MMIC itself.

The last point is critical for the work that must be done. A factor of two in noise is simply too much to give up in going from individual amplifiers to array building blocks.

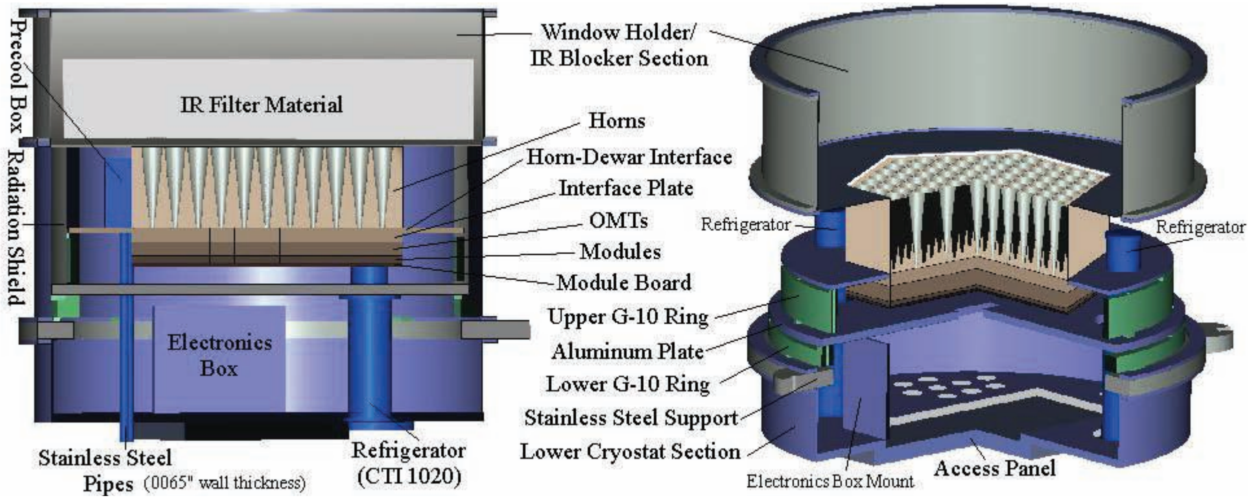

FIG 15.—Sections of the QUIET cryostat, showing how a 91-feed platelet array, OMTs, and modules are arranged. The modules are placed in standard pin sockets on circuit boards. The size envelop for a given polarimeter module is limited by the spacing of the corrugated feeds, whose size is determined by the optical system. [Laura Newburgh, Columbia]

3.3 Development Plan

In the previous sections we have identified two critical areas of development needed to realize the full promise of coherent instruments for CMB polarization in space. (The reader is reminded that as shown in Figure 1, coherent systems have already achieved noise performance significantly better than bolometers from the ground.) These are:

- Improving the performance of individual transistors and MMICs to at least the level predicted to be achievable with 35 nm gate technology (Figure 11), and perhaps even further.
- Integrating high-performing MMICs into the building blocks of large arrays without loss of performance. Currently a factor of two or so in both noise and bandwidth is lost at this step.

We discuss these in §§ 3.3.1 and 3.3.2 below.

3.3.1 Device and MMIC level issues

To achieve noise of $\leq 3 \times q$ from 30 to 150 or 200 GHz, a range important for CMB polarimetry, we can identify known issues and potential innovations that should be addressed.

Figure 12 shows a preliminary top level research plan. There are three main thrusts.

- Measure and study existing devices and circuits for cryogenic performance and behavior to improve device physics understanding, and to guide and focus the future device development.
- Develop new devices, with at least three iterations of experimental runs. At the end of each run, benchmarking and analysis will inform the next run. The results from these runs will feed into the third main thrust
- Two amplifier design iterations and fabrication runs to demonstrate amplifiers with improved cryogenic performance. This type of comprehensive study to optimize HEMTs for cryogenic noise performance should enable reaching the ultimate limit for these devices, which may require new devices and materials not currently available.

Performance improvements will require addressing or solving the following issues, which are likely performance limiters.

Shot noise due to excessive gate leakage—In pursuit of the highest gain and transconductance InP HEMT devices, excessive leakage current at operating conditions limits the ultimate

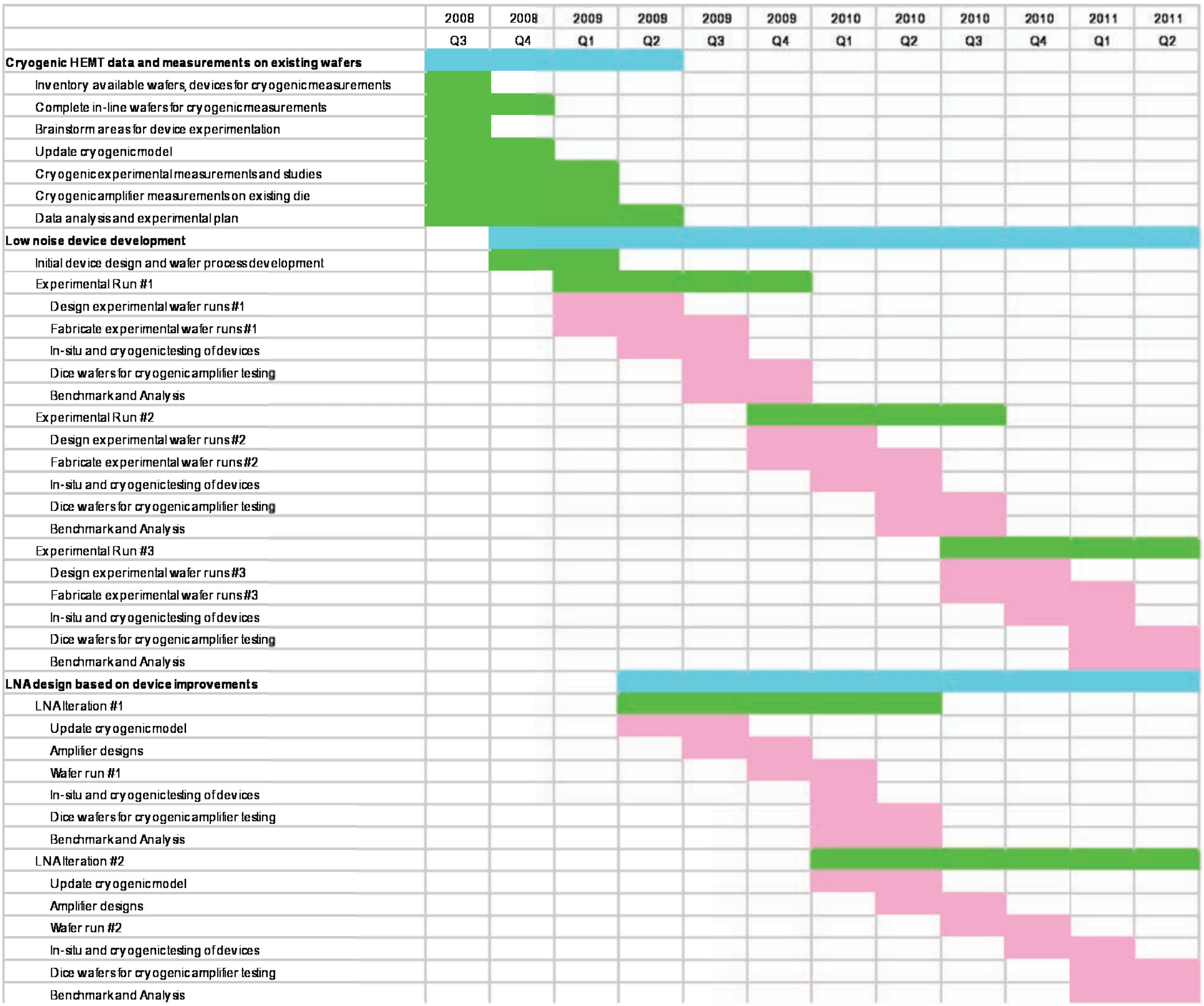

FIG 16.—Top level program plan to achieve noise temperature goals.

noise performance, especially at low frequencies where thermal noise is extremely reduced. Current research into alternate gate metals, barrier designs, gate recess chemistries and etch stops may improve both the turn-on voltage and reverse gate leakage for the InP HEMT devices while maintaining the other key dc and rf parameters. Of greatest interest is reduction of gate leakage at cryogenic operation which has not been studied or optimized carefully. NGST and JPL have observed wafer to wafer and lot to lot variation in the gate leakage. Although not as important currently at higher frequencies, future improvements in device performance at higher frequencies will necessitate low gate leakage below 1 μA to realize the next levels of noise performance.

High ohmic resistance at cryogenic temperatures—Recent investigations have shown that current InP HEMT ohmic contacts are not optimal and studies of the ohmic contact resistance to cryogenic temperatures may be important. This will have an impact not only on device gain, but also on the optimal dc bias voltage/current needed to achieve usable gain and its effect on drain temperature. Alternate ohmic contact and epitaxial schemes look promising for $> 2\times$ improvement, which may translate directly to cryogenic device noise improvements. Limits of epitaxial doping and design have also not been explored, especially for cryogenic operation.

Anomalous cryogenic HEMT behavior—Although not consistently observed, known potential issues such as IV kink at cryogenic temperatures (light sensitive), high output conductance, poor device pinchoff, low breakdown devices, high leakage and gain fluctuation need to be understood and avoided. Customized cryogenic tests can be developed to study these occurrences and how to avoid them. In some areas, promising room temperature solutions have been developed and it will be benefitial to translate these improvements to cryogenic products.

InP HEMT yield limiters—Ohmic contact and sheet resistance, gate yield and defects, device breakdown, gate leakage, damaged airbridges, via hole yield, back metal adhesion, TFR damage, probe and metal scratch damage, dicing (splitting die), wafer breakage, and line errors are all factors.

Cryogenic device and noise models—Pospiesalski's cryogenic model is simple and predicts fairly well the noise parameters and overall performance of low noise amplifiers, especially for discrete device amplifiers. Updates to this and other alternately improved cryogenic HEMT noise models are important for future designs to improve ultimate noise performance

Over the past several years, NGST has innovated advanced semiconductor materials, epitaxial designs, ohmic, gate and interconnect metals, device topologies, passivation thickness and interfaces, and backside wafer process improvements for its HEMT devices. The central focus for these advances at NGST continue to be to improve room temperature noise figure performance of LNAs with at times the lowest dc power consumption and further system advantages in size and weight that can be derived through higher frequency implementations. These products are primarily aimed towards insertion into NGST's satellite communication payloads. To spur these innovations, NGST has invested significant internal R&D funding for device and MMIC research (totaling more than \$10 M/year) and has consistently won contract R&D funding mainly from DoD services (also totaling more than \$10 M/year) over various semiconductor devices and products. NGST also continues to invest a large amount of semiconductor equipment capital also easily exceeding \$10 M/year) especially to develop these novel materials and device processes.

What has not been studied recently is how these advances may spur improvements in the cryogenic operation of these devices. It can be projected that the room temperature improvements especially in noise performance may translate to improvements with cryogenic operation, but a careful engineering study and optimization have not been conducted to date. Listed below are key innovations both near and long term that can improve the state-of-art for cryogenic noise performance.

Nanometer-scale gate length reduction—Short gates (70 nm and 35 nm) have demonstrated reasonable yield and reproducibility in combination with optimized epitaxial profile designs for each of these nodes. The use of these device technologies has focused mainly on a new generation of amplifiers from 140 GHz to 400 GHz, but extremely high device gain may also provide distinct low noise advantages at any frequency where the device and amplifier noise performance is potentially gain limited.

Atomic scale material growth and design—Advanced HEMT materials may offer higher frequency operation and low noise performance. Electron transport in InGaAs channels grown pseudomorphically on InP substrates has been improved with InAs channels (100% Indium) through the design of a composite channel epitaxy design. Extremely high room temperature mobilities of 16,000 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$, which represents a 30–50% increase compared to the baseline 60% InGaAs channels, have been observed. Further study of these devices is necessary with the potential of alloy scattering and impact ionization dominating with cryogenic operation. ABCS (Antimonide-based Compound Semiconductor) devices employing metamorphically grown InAs and potential InAsSb channels represent future material innovations that could push mobilities and electron velocities to even higher values. Limited cryogenic data have not achieved new state-of-art performance as current challenges in material quality, high leakage, and impact ionization still need to be addressed.

Device parasitics—Significant improvements have been made recently in ohmic contact and access resistance, in both epitaxial designs and new refractory ohmic metals. Contact resistance improvement by as much as 3× and sheet resistance improvement of 50% have been achieved on the most aggressive devices at room temperature, and should benefit cryogenic operation and low noise performance. Further development and exploration of sheet resistance limits through new epitaxial designs and smaller ohmic-to-gate spacings, including self-aligned gate device schemes, should be part of further work. Reduction of resistance in cryogenic operation is critical for lowering operating drain currents and voltages for high gain, which ultimately reduces drain temperature in the standard cryogenic FET model. Innovations for reduction of capacitance parasitics with both alternate low dielectric constant passivation films and thinner passivation films should be explored. The latter has been employed on recent high frequency devices and should be studied for potential benefits with cryogenic operation.

HEMT gate innovations—For HEMT devices, the gate process and metal-semiconductor junction remains the most critical in determining device performance. Barrier height and threshold voltage are crucial in optimizing device transconductance and gain, but breakdown and leakage current must be controlled to enable a useable device. Often these requirements conflict and the trades are even less understood at cryogenic operations where certain leakage currents are suppressed, while others are enhanced. The gate recess process formation is equally critical as it impacts breakdown, leakage and access resistance. Many of the effects and variations with cryogenic operation have not been carefully studied and optimized. Several innovations are being explored. New refractory gate metals, especially Mo and TiW, are being explored that may provide lower leakage and superior cryogenic Schottky junctions. Controlled interdiffused junctions that could reduce $1/f$ noise for cryogenic operation have not yet been explored. Epitaxial growth is still critical, and although not studied to date, heterostructure and doping interface sharpness may be critical to determine limits on gate-to-channel separation, where we face tradeoffs between transconductance and gain vs. excess leakage and degraded Schottky junctions. Combined with new refractory metals, the trade space should be explored for optimal cryogenic performance. Tailoring the gate recess profile through etch stops and multiple recess steps may provide advantages where the designs are aimed towards cryogenic low noise operation. However, current research is aimed more towards higher power, higher device density circuits. Barrier layer epitaxial designs for both etch stop and bandgap engineering should be studied more carefully for cryogenic optimization. As an example, current ABCS HEMT device utilization is limited due to manufacturing issues of the gate barrier layer AlSb and GaSb.

New devices, materials, ideas—The advent of new transistors and materials as they come to some level of maturity and utility may be crucial to achieving the noise goal $\leq 3\times$ quantum limit or even beyond. Among the promising technologies being pursued are quantum wire devices, as well as carbon nanotube and graphene transistors. Nanolithography will also push the limits on device scaling and we anticipate research in smaller gate length nodes down to 20 nm or less to achieve amplifiers that could operate as high as 1 THz in the future. Optimizing these types of concepts for cryogenic noise operation may also reveal unexpected and further performance breakthroughs.

3.3.2 Module level issues

The key is to realize the full performance potential of the transistors and MMICs in a unit cell package that enables massive arrays. This requires cryogenic measurement and characterization of MMICs and other components, isolation of the critical factors in performance, design and fabrication iterations, and exquisite control of fabrication.

An essential point that must be emphasized again is that while there is substantial commercial and military interest in coherent detectors for communications and imaging, there is little interest outside the astronomical world for *cryogenic* applications. The development for CMB polarimetry of array building blocks with no loss in MMIC performance is inherently cryogenic. Easy cryogenic, at only 20 K or so, but cryogenic. The commercial world will not provide this development.

The work will involve both MMIC amplifier design and prototype multichip MMIC module development. A simple mask set with transistor test cells, simple MMIC test amplifiers, and space for new MMIC designs, must be developed. Multiple iterations of design, wafer processing, test and characterization, and module fabrication will be required. Based on recent history, there is no reason to expect that fundamental technological breakthroughs will be required, but clearly careful attention to engineering details will be essential, and a lot of work.

3.4 Assessment

The TFCR recommended:

- “Technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors.. . .It is important to keep open a variety of approaches until a clear technological winner has emerged.”
- “A strategy that supports alternative technical approaches to detectors and instruments. Advances in CMB science have been based on a variety of technologies. Though we expect that bolometers will be the clear choice for CMBPOL, it is premature to shut down the development of alternatives. We recommend the continued development of HEMT-based detectors as they might lead to an alternative space mission and will certainly be used in ground-based measurements.”

The noise projected for amplifier systems has changed dramatically since the TFCR deliberated, when the expectation for amplifier noise at 140 GHz was too high to list in their table. This elevates the importance of the TFCR recommendation to support multiple approaches including HEMT-based detectors. Transistors now exist that far exceed the performance of anything that existed or was projected in 2005 at millimeter-wave frequencies.

4 HETERODYNE INTERFEROMETRY

4.1 Introduction

Heterodyne interferometers have a long heritage in ground-based measurements of the Cosmic Microwave Background radiation, with the DASI experiment making the first detection of CMB polarization, and the CBI making some of the first measurements of the shape of the E-mode power spectrum. Both DASI and CBI also made detailed measurements of the CMB temperature power spectrum, detecting multiple peaks in the power spectrum prior to the launch of WMAP. Interferometers have some attractive features that make them particularly suited for measurements of B-mode polarization: a) each baseline of the instrument is sensitive directly to a particular Fourier mode on the sky, so the measurements are made direcly in Fourier space; and b) they measure both amplitude and phase, so the real and imaginary parts of the signal can be combined in a straightforward way to decouple the E and B mode signals accurately.

Figure 6 shows schematically how this is accomplished. A cross-correlation between the circularly polarized states, one from each antenna, is formed. The visibilities that correspond to the cross-correlations are related to the Stokes parameters as follows (Kovac et al., 2002).

$$V^{RR}(\mathbf{u}_i) = \alpha_i \int d\mathbf{x} A(\mathbf{x}, \nu_i)[T(\mathbf{x}) + V(\mathbf{x})]e^{-2\pi i \mathbf{u}_i \cdot \mathbf{x}},$$

$$V^{LL}(\mathbf{u}_i) = \alpha_i \int d\mathbf{x} A(\mathbf{x}, \nu_i)[T(\mathbf{x}) - V(\mathbf{x})]e^{-2\pi i \mathbf{u}_i \cdot \mathbf{x}},$$

$$V^{RR}(\mathbf{u}_i) = \alpha_i \int d\mathbf{x} A(\mathbf{x}, \nu_i)[Q(\mathbf{x}) + iU(\mathbf{x})]e^{-2\pi i \mathbf{u}_i \cdot \mathbf{x}},$$

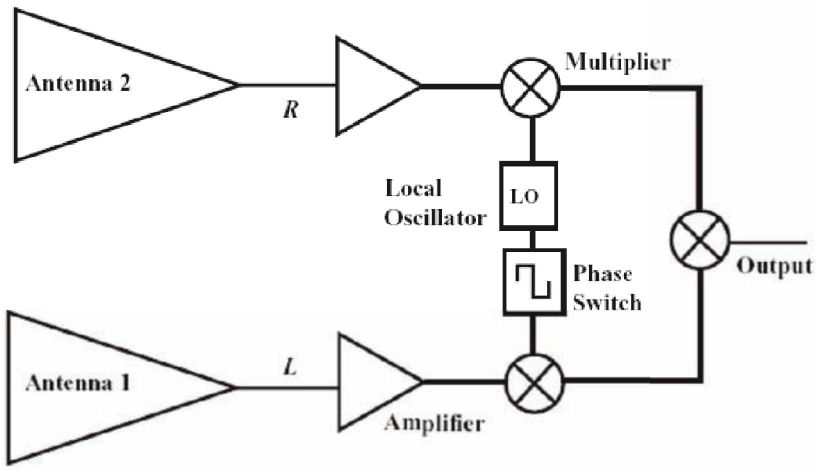

FIG 17.—Schematic of the operation of an interferometer (from Staggs and Church). A single polarization state from one antenna (in this case circular) is correlated with the polarization state from a second antenna. Placing a OMT after the feedhorn to split the signal into left and right circular polarization states, with a separate amplifier chain for each, allows all four Stokes parameters to be measured.

$$V^{RR}(\mathbf{u}_i) = \alpha_i \int d\mathbf{x} A(\mathbf{x}, \nu_i)[Q(\mathbf{x}) - iU(\mathbf{x})]e^{-2\pi i \mathbf{u}_i \cdot \mathbf{x}},$$

from which the E and B components can be reconstructed:

$$\tilde{Q}(\mathbf{u}) = \cos(2\chi)\tilde{E}(\mathbf{u}) - \sin(2\chi)\tilde{B}(\mathbf{u}),$$

$$\tilde{U}(\mathbf{u}) = \sin(2\chi)\tilde{E}(\mathbf{u}) + \cos(2\chi)\tilde{B}(\mathbf{u}).$$

It is also possible to build an interferometer based on bolometric interferometry by combining the signals optically prior to detection on a bolometric array. Such an approach is discussed elsewhere in the workshop. However, coherent amplifier technology is more suited to interferometric measurements that bolometric technology because the former has the ability to replicate photons, once the quantum tax is paid, allowing the full polarization state of the incoming radiation from a single feed to be explored without degrading the sensitivity. In contrast, a bolometric interferometer cannot simultaneously measure Q and U (and thus E and B). Instead the incoming polarization state must be optically modulated, a complicated technology development that is not required in a coherent amplifier interferometer.

The advantages of interferometry do not lessen the need for sensitivity. Large arrays of detectors operating near fundamental noise limits are required whether the detectors are treated independently or as part of an interferometer. Since a close-packed interferometer and a close-packed focal plane array with the same number of elements have the same sensitivity, a B-mode interferometer needs hundreds of array elements per frequency just like a focal plane array. Fortuitously, a close-packed interferometric array with hundreds of elements to satisfy the sensitivity requirement also has an extremely well-shaped synthesized beam with very low sidelobe levels. This is the kind of interferometer that we are discussing.

4.2 Systematics and Sensitivity: Advantages and Disadvantages

Because an interferometer directly measures the spatial correlation function of the incoming signal, the measurement technique is fundamentally different from that of focal plane arrays.

Advantages:

- Coherent-amplifier interferometric methods allow certain systematics to be greatly reduced or to be absent all together without the need for complicated multi-parameter modeling. Table 3 shows a list of systematics and a comparison of their effect on an interferometer with a system based on a focal plane array of bolometers. Note that many of these advantages are lost in a system based on bolometric interferometry.
- The cross-correlation of a single polarization state from two different antennas measures a single Fourier mode on the sky. Uncorrelated signals, such as amplifier $1/f$ noise, are strongly suppressed.
- There is inherent differencing involved in the cross-correlation process. The fringe pattern that is formed on the sky filters the images in ℓ-space in a well-understood way.
- A single Fourier mode is measured with just two detectors, which simplifies the mode-by-mode calibration in ℓ-space. Note that this advantage is lost in a bolometric interferometer, where the fringes are projected onto a bolometer array and many detectors are required to measure a single mode.
- With hundreds of close-packed corrugated horn elements, the synthesized beam will be both extremely clean and calculable with high precision. Moreover, the radiation pattern of individual corrugated feeds, which adds up to the envelope of the "primary beam", is better than that of any telescope. Beamshape uncertainties with telescopes are a major systematic affecting current experiments. WMAP, for example, continues to make beam corrections at the 1% level or so that affect science results directly. *The impossibility of fully characterizing the feed+telescope patterns with high dynamic range in the post-launch, cold environment of space may provide an ultimate limitation to telescope+focal plane array experiments. An interferometer seems likely to avoid this problem (detailed analysis is needed to quantify this), and as a result seems to be the ultimate in low systematics for CMB polarization.*
- The noise modeling is simplified by the interferometric strategy because the noise from a single baseline is localized to a specific point in Fourier space.
- Because the angular resolution requirements are modest, corrugated feed horns can be used as the antennas, with the result that sidelobes and cross-polarization will be the lowest that is possible for any of the proposed B-mode experiments at the present time.
- A heterodyne interferometer can be configured in a natural way as a broad-band spectrometer by splitting the IF band into N_{sub} spectral bands. Depending on the requirements that this places on the downlink speed, this spectral information can be retained and used as a check on systematics from foregrounds.

Disadvantages:

- An interferometer filters out all angular scales larger than the primary beam. This sets a lower ℓ limit to the interferometric measurement; however, the total power signal from the feeds could be used directly to measure the lowest multipoles. Work would be required to figure out the best way to do this, and this complication makes it appropriate to consider this a disadvantage of an interferometer. The silver lining is that the low ℓs would be measured without a telescope, which will reduce systematics.

Considerations & Practicalities:

- Cross-talk or mixing between polarization states in the same antenna can lead to leakage of T into Q and U. This can be mitigated by phase switching the two states at different frequencies. Unlike the complex phase modulation required for bolometric inteferometer, a simple 180 degree phase switch—a mature, well understood technology—is used. Cross-talk that occurs between the antennas and the phase switch is mitigated by enclosing the low-noise amplifiers in separate metal housings. Cross-talk between antennas can be mitigated by scanning the instrument across the sky to modulate the sky signal with respect to the more slowly varying cross-talk.

- The number of pixels that can be accommodated in a space-based interferometer will be limited primarily by power dissipation and the capabilities of the correlator.
- At 150 GHz and above, the noise temperature of the heterodyne system will be significantly higher than a bolometric system, but the foreground signals, which are the primary target at higher frequencies, are also rising. As discussed in § 2.2, preliminary indications from modeling of component separation are that optimum results are obtained when noise per channel is proportional to total signal, including foregrounds.

TABLE 3

A Comparison of the Effects of Systematics on Bolometric and Coherent Interferometers

Systematic	Effect in: Bolometer Int.	Effect in: Coherent Int.	Mitigation in Coherent Interferometer
Crosspolar beam	E to B	E to B	Corrugated feed horns have very low crosspolar response
Polarization angle errors	E to B	no leakage	Because each pixel images the entire primary beam, errors in polarization angle change u-v point the location but do not rotate E into B
Pointing errors (on Q/U)	E to B	N/A	Not present (Q, U from same feed)
Main beam asymmetry (before differencing)	ΔT to B	ΔT to B	Corrugated feed horns have highly symmetric beams
Sidelobes	ΔT to B	ΔT to B	Corrugated feed horns have very low sidelobes. Large scale structure in sidelobes is attenuated further by coherence length effects in the interferometric process.
Instrumental polarization (optics)	ΔT to B	ΔT to B	Corrugated feedhorns have very small effect. Measure.
Instrumental polarization (receiver)	ΔT to B	ΔT to B	Measure pre-launch.
Relative calibration errors	ΔT to B	no leakage	Feed to feed gives calibration error on amplitude of E and B. Calibrate.
Pointing errors before differencing	T to B	N/A	Absent. No differencing
Gain drift before differencing	T to B	N/A	Absent. No differencing
Optics and spillover T variations	$\delta T_{\rm opt}$ to B	$\delta T_{\rm opt}$ to B	Corrugated feeds have extremely low spillover. Attenuated by coherence length effects in interferometric process
Scan modulated cold stage variations	$\delta T_{\rm CS}$ to B	N/A	No effect in an interferometer
Band shape errors, including modulator effects	Foregrounds to B	Foregrounds to B	Band shape can be flattened in data analysis (sub bands)
Primary Beam Uncertainty	Tilts power spectrum by affecting window function at large ℓ	Fourier space measurement with identical window functions at all ℓ. Just affects overall calibration of spectrum	

4.3 Technical Design and Technology Development Program

In order to achieve the noise levels required to measure B-modes, both the sensitivity and the number of individual detectors/interferometer elements must be increased. The sensitivity of a filled-array interferometer and a close-packed focal plane array with the same angular resolution and sensitivity per detector are the same. Therefore, from a detector standpoint the same basic requirements apply to interferometers and focal plane arrays, namely, better detectors, and more detectors. he number of interferometer elements must be increased from the dozen or so of past CMB interferometers (e.g., VSA, DASI, CBI) to hundreds. This simultaneously produces a synthesized beam with extremely low and symmetric sidelobes.

In this section we discuss the technological developments required specifically for the application of amplifiers to an interferometer.

Compact heterodyne radiometers—The development of compact millimeter radiometers has many applications in both astronomy, earth observing, and of course, communications. The development of compact cryogenic heterodyne radiometers benefits many astronomical programs, not only CMB polarization measurements. These include ground based high-resolution interferometry, and both ground and space-based spectrometers. Developments in the miniaturization through MMIC technology of key components such as mixers, filters, phase switches (and of course the low-noise amplifiers themselves) allows for the fabrication of a large interferometric array based on compact modules and high-frequency printed circuit board. Figures 7 through 9 show a design that is currently in the prototyping stage.

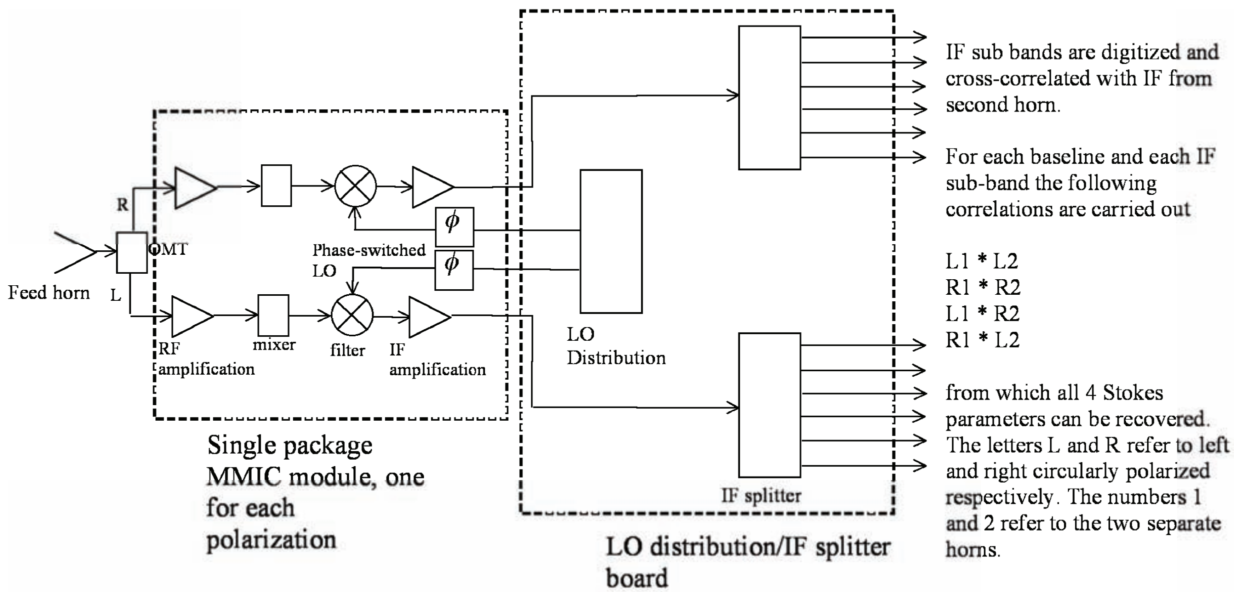

FIG 18.— Schematic of a single pixel suitable for use in an interferometer to measure CMB polarization.

Correlator technology—The number of required correlations at a given frequency is:

$$N_{\rm cor} = \frac{N_{\rm feed}(N_{\rm feed}-1)}{2} \times 4N_{\rm sub} \approx 2N_{\rm feed}^2 N_{\rm sub},$$

where $N_{\rm feed}$ is the number of pixels, $N_{\rm sub}$ is the number of IF sub-bands, and the factor of 4 comes from the requirement to correlate LL, RR, LR, and RL, where R and L are the two polarization states. The number of sub-bands will be determined by the need to avoid chromatic aberration, and by the clock speed of the digitizer.

Recent technology developments with space-based cross-correlators for Fourier synthesis interferometers have been driven by several proposed Earth Science remote sensing missions, in particular the Lightweight Rainfall Radiometer (LRR) and the Geosynchronous Earth Orbit Synthetic Thinned Aperture Radiometer (GEOSTAR). In both cases, emphasis has been placed on reducing the power requirements, increasing the clock speed, and improving the radiation tolerance

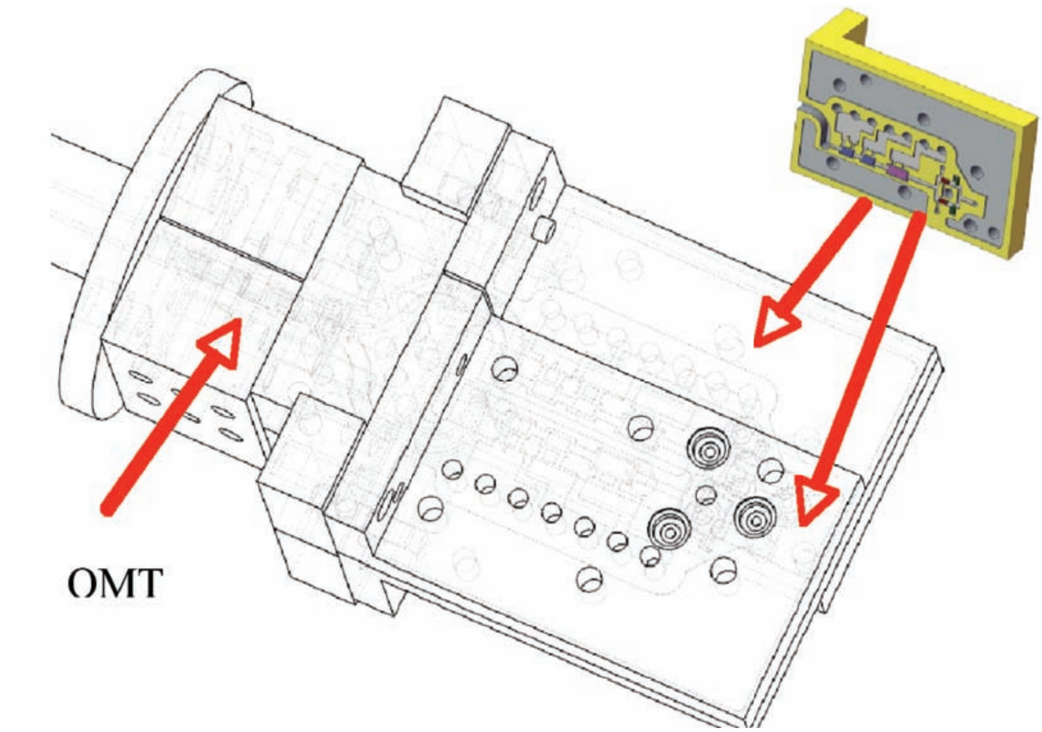

Fig 19.—Two MMIC modules are used, one per polarization.

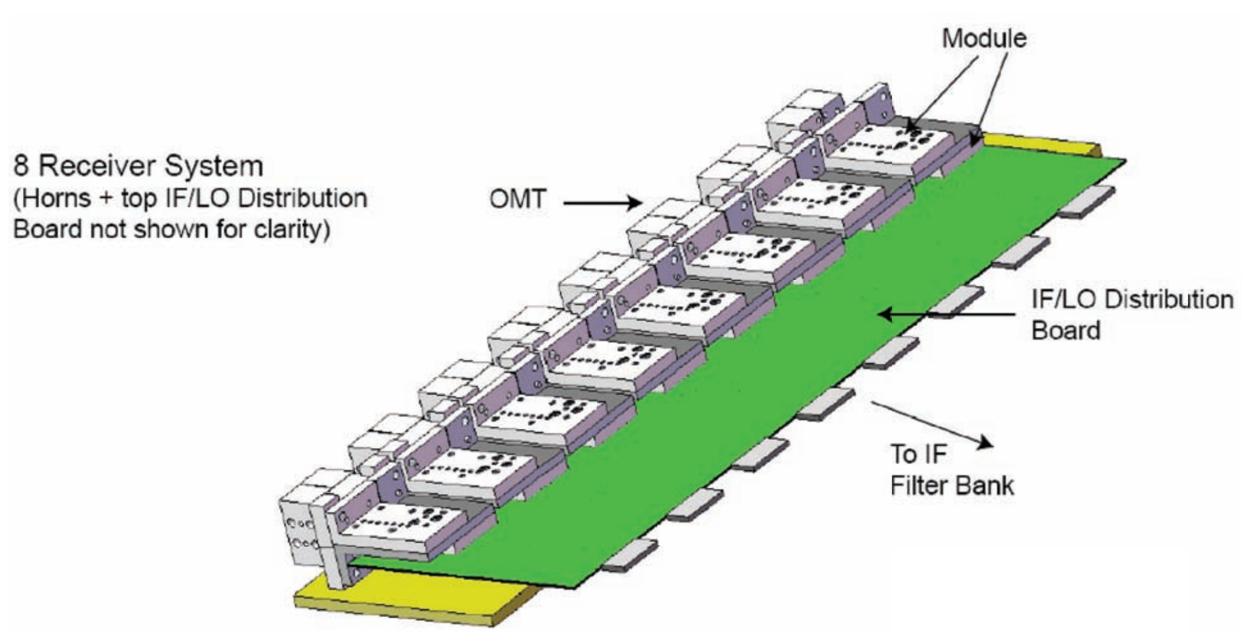

Fig 20.—The modules are mounted on the IF/LO distribution board, which will further amplify the IF signals. There are two boards, one for left circular, and the other for right circular, polarization but the upper board has been omitted for clarity.

of the digitizers and the multipliers/accumulators through the use of ultra-low power CMOS ASICs based on a 0.5 V logic protocol with resistance by design to radiation-induced single event upsets. This protocol has extensive spaceflight heritage for other high speed digital signal processing applications in space.

The new multiplier/accumulator for the GEOSTAR project is being built using a 90 nm CMOS

ASIC process. It is projected to be capable of complex cross-correlations of all possible pairs of 196 In Phase and 196 Quadrature Phase 2-bit input signals, clocked at 1400 MHz, while drawing 1.68 W of DC power.

Scaling from these chips, the power for multiplier/accumulators for a CMB application given current mature technology would be given by

$$P = 98 \left(\frac{N_{\rm el}}{196}\right)\left(\frac{\Delta\nu}{19.8\,{\rm GHz}}\right)\,{\rm W}.$$

Additionally we need to consider the digitizers. If the IF bands are 1.4 GHz, then the digitizer needs to run at 2.8 GHz for Nyquist sampling. Low-voltage digitizers that operate at this clock speed have not yet been demonstrated, but a 1-bit digitizer clocked at 392 MHz has been demonstrated that dissipates 4 mW. Assuming that the power dissipation scales with clock speed *(is this right?)* the power dissipation would be

$$P = 40 \left(\frac{N_{\rm el}}{2}\right)\left(\frac{\Delta\nu}{19.8\,{\rm GHz}}\right)\,{\rm W}.$$

Future Technology and Recommendations—Further reductions in the power required of, and further increases in the maximum clock rates supported by, the ultra-low power 0.5 V CMOS ASICS will be possible as the design rules decrease further in size. Preliminary developments are underway at 65 nm for other, non Earth science, applications and are expected to continue. These developments should eventually mature to the point where they can be leveraged for our application. An acceleration in that development process would require additional infusion of funds. Leveraging of the current 90 nm process for the development of faster and/or lower power digitizers than those developed for LRR has lagged behind that for the multiplier/accumulator chips. In order to maintain a reasonably close match between the maximum clock rate capabilities of the digitizers and multipliers/accumulators, it is recommended that additional development funds be considered for the digitizers. In particular, development is recommended of 90 nm versions of the LRR-style digitizers. Based on the modeling projections made for the 90 nm multiplier/accumulator ASICs, this can be expected to result in digitizers with maximum clock rates in the neighborhood of 1400 MHz. By comparison, current flight qualified digitizers capable of $\sim$2 GHz clock rates require $\sim$2 W of power to operate. The power needed is much too high to be supportable for typical large N interferometer systems. A 90 nm ultra-low power 0.5 CMOS ASIC digitizer can be expected to reduce the power required by two orders of magnitude.

4.4 Technological Readiness

4.4.1 Cost and Timescale to bring to TRL 5

The development of prototype pixels is already underway and involves:

- Development of the cryogenic MMIC module. The first prototypes have been fabricated and are expected to be tested before Jan 2009. Note that this work is currently underway with the goal of astronomical spectroscopy as well as CMB measurements, reducing the overall cost.
- Development of the IF/LO splitter board. This is in the design phase. We expect the first prototypes to be produced and tested by Jan 2009. Note that this work is currently underway with the goal of astronomical spectroscopy as well as CMB measurements, reducing the overall cost.
- End to end testing of a single baseline prototype, using an existing FPGA correlator design. the tests will include a demonstration of low pixel-pixel cross-talk, low noise and good separation of the polarization states.

TABLE 4

Technology with Applications Beyond Interferometry

Element	Heritage	Development Needed for CMBPol	TRL	Comments
Feed horn array	WMAP, Planck feed designs	Test crosstalk on very small baselines	6^+	The behavior of individual feed horns is well understood from WMAP, Planck. Platelet arrays will be fielded in QUIET.
	Platelet arrays for QUIET	Weight reduction		
Orthomode transducers	WMAP, QUIET	Weight reduction, assembly of many unite.	6^+	
20 K Cooler	Planck		9	

TABLE 4

Technology with Applications Beyond Interferometry

Element	Heritage	Development Needed for CMBPol	TRL	Comments
Heterodyne MMIC amplifier modules	QUIET radiometers, Geostar heterodyne MMICs	Prototype pixel fabrication	4	Prototype single polarization heterodyne module is under development. Paper design exists, fabrication expected by end 2008.
	Platelet arrays for QUIET	Weight reduction		
IF electronics		Low power amplifiers		Use HEMTs?
Correlator	Geostar development	low power ASIC correlator chips and digitizer	4–6^+	

TABLE 4

Cost and Timescle for Prototype Development

Element	Goal	Timescale	Cost
Heterodyne MMIC amplifier modules	Tests of single prototypes	Jan 2009	100K
IF/LO Splitter board	Design and Testing	Jan 2009	100K
End to end test	2-element prototype	Sep 2009	200K

The estimated cost to complete this program is $\sim 400\,\mathrm{K}$, broken down in Table 4.

The next stage is the deployment of 100-pixel arrays at a good ground-based site at each of the key frequencies. The goal is the deployment of the first array in FY2010 with remaining arrays in 2011, at an estimated cost of 500K/year.

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