Development of Focal Plane Arrays Utilizing NbN Hot Electron Bolometric Mixers for the THz Regime

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***ABSTRACT* -** Improvements in device development and quasi-optical coupling techniques utilizing planar antennas have led to a significant achievement in low noise submillimeter wave receivers at progressively higher frequencies. Hot Electron Bolometric (HEB) receivers made of thin film superconducting films such as NbN have produced a viable option for instruments designed to measure the molecular spectra for astronomical applications as well as in remote sensing of the atmosphere. Total system DSB receiver temperatures of 500 K at 1.56 THz and 1,100 K at 2.24 THz were measured since the last STT Symposium. These results are 13 and 20 times the quantum noise limit at the respective frequency (the DSB quantum noise limit (hf/2k) is about 24 K at 1 THz). Typical best performance for Schottky barrier mixers is about 100 to 200 times the quantum noise limit. The technology of NbN Hot Electron Bolometric (HEB) mixers is progressing from the one pixel platform into a multi pixel system and special considerations of the new requirements for such devices is emphasized. One important characteristic is the LO power consumption which is in the hundreds of nanowatts range and, therefore, makes NbN HEB mixers excellent devices to integrate with a number of promising power sources under development as well as available technologies. Furthermore, new developments are under way which will decrease the optical and microwave coupling loss further; in particular, improvement of the RF match of the device to the antenna, optimization of the input impedance of the IF amplifier, and further improvement of the NbN film active medium quality. Preliminary study of MgO substrates shows an improved IF bandwidth. IF noise bandwidths in excess of 10 GHz are expected in the near future.

The recent results reported here make the development of focal plane arrays with tens of HEB mixer elements on a single substrate for real time imaging systems in the THz region an achievable goal.

I. INTRODUCTION

The development of low-noise receivers in the THz frequency region is primarily motivated by the need for low noise and low power consumption receivers for the next generation of space-based and airborne astronomical observatories (FIRST, SOFIA, etc.), as well as space-based remote sensing of the Earth's atmosphere (EOS-MLS). Until a few years ago, the only heterodyne receivers available for the THz region utilized nonlinear frequency-conversion devices which were either GaAs Schottky Barrier Diodes (SBD) or InSb Hot Electron Bolometers (HEB). THz SBD mixer technology has recently made a transition from cumbersome whiskered diodes in corner-cube mounts to planar versions in waveguide. The Double SideBand (DSB) receiver noise temperature of SBD mixer receivers has remained essentially stationary at about (100-200)x hf/2k [1] (hf/2k is the quantum limit for DSB receiver noise temperature and is about 24 K at 1 THz). Fabrication technology and material parameters limit the size of the monolithic junction and therefore limit the noise temperature performance. In addition, SBD receivers require a few mW of LO power. InSb mixers have always been too restricted in bandwidth (only about 1 MHz) for most applications. Below 1 THz, SIS (Superconductor/Insulator/Superconductor) mixer receivers have excellent noise temperature (only a few times the quantum noise limit). The noise performance is limited to frequencies below or about equal to the superconducting bandgap frequency.

Hot Electron Bolometric (HEB) mixers, which use nonlinear heating effects in superconductors near their transition temperature, have become an excellent alternative for applications requiring low noise temperatures at frequencies from 1 THz up to the Near IR. There are two types of superconducting HEB devices, the Phonon-Cooled (PC) version [2], and the Diffusion-Cooled (DC) version [3][4]. At present, most of the lowest recorded receiver noise temperatures have been obtained with the PC type HEB [5][6], although the difference is not very large. This paper only describes the development of the PC HEB. Superconducting HEB mixers also require much less LO power than SBD receivers (100 nW to 1 μW for PC HEBs). The only practical LO source, presently available, is an FIR gas laser although solid state LO sources with sufficient amount of power are under development and will be available in the future. The present state-of-the-art of different THz receivers is compared in FIG. 1.

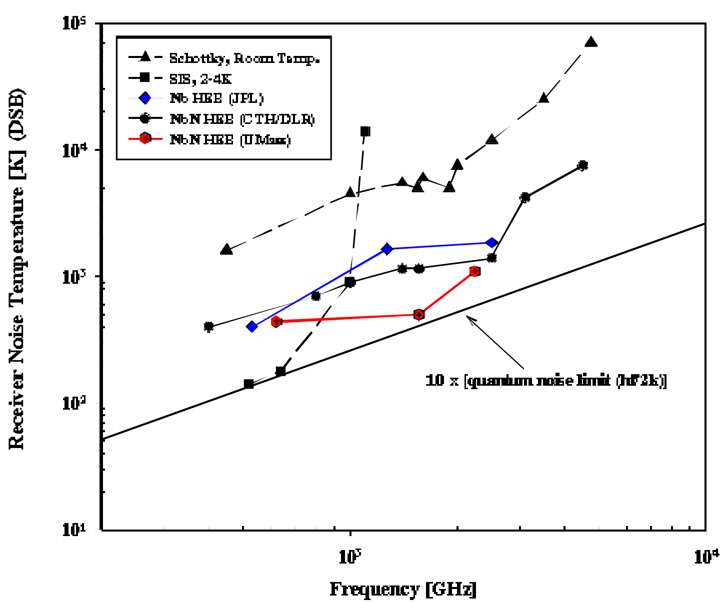

FIG. 1. Noise temperatures as a function of frequency for receivers in the terahertz regime.

The conversion gain and output noise of an HEB mixer can be calculated using what has become the "standard" model for HEB devices [7][8]. It is found that there is an optimum amount of LO power which yields the minimum noise temperature. In practice the optimum receiver noise temperature occurs for a bias current which is about 30 - 40 % of the current in the resistive region of the I-V curve without LO power. The standard model, which assumes a uniform electron temperature, is useful for a first order description of the PC HEB, but can not give a complete description of the device. New models for the mixer operation for frequencies in the terahertz regime assuming non-uniform electron temperature are under investigation [9].

The IF bandwidth for the conversion gain is determined by the thermal time-constant (τ_m) of the HEB device. The HEB dissipates the power it absorbs through a two-stage process: the heated electrons first emit phonons, which will then be transmitted through the film/substrate interface into the substrate. An interface resistance due to phonon mismatch has to be taken into account, and this resistance varies with the substrate upon which the thin film is deposited. To maximize the IF bandwidth, the film should be as thin as possible while still having good superconducting properties (high T_c and low ΔT_c). The mixer time-constant (τ_m) also includes a factor which depends on the self-heating of the bolometer [7]. The receiver noise temperature bandwidth (B_{NT}) is wider than the conversion gain bandwidth (B_G). The fact that the receiver noise temperature bandwidth is two to three times wider than the conversion gain bandwidth is a well-known feature of HEB mixers. This characteristic can be understood if one realizes that the main noise process in the device (temperature fluctuation noise) yields a noise output which falls at the same rate as the conversion gain, flattening the net receiver noise dependence on the IF frequency.

II. DEVICE DESIGN AND FABRICATION

A typical HEB device is made from a thin (3 to 4 nm) film of NbN deposited on a substrate of silicon, quartz, sapphire or MgO by DC magnetron sputtering. Thinner films are desirable in order to achieve wider IF bandwidth. The critical temperature of the NbN film is about 10 K, depending on film quality and thickness, and efficient mixing occurs at about half that temperature. Much effort has been spent on improving the quality of the NbN films, which is especially critical for the thinnest films. Above the superconducting bandgap frequency (roughly 1 THz for these films), terahertz radiation sees a resistance roughly equal to the normal resistance, which is 300 Ω/square to 600 Ω/square. A device with an aspect ratio (length to width) of from 1:5 to 1:10 will therefore match a typical antenna impedance of 75 Ω. The critical current of a device is a few hundred μA, while a typical DC bias voltage is 1 mV. Since the device acts as a bolometer, the absorbed LO power, which is a function of the device area, is measured by the device itself and is computed from its I-V curve. Our devices have a length of 0.6 to 1 μm and LO power from 0.5 to 1 μW.

Quasi-optical coupling is very convenient at the very high THz frequencies where waveguides become increasingly difficult to manufacture. We couple our devices through a 4 mm diameter elliptical lens made from high-purity silicon. In order to facilitate testing over a wide range of frequencies, we have initially used a log periodic self-complementary toothed antenna. This design is scaled from the millimeter wave design in [10] and is illustrated in FIG.2. Other antennas under investigation in a number of laboratories are spiral antennas, twin dipole/slot antennas, and slot ring antennas. We have used a log-periodic antenna with a maximum frequency of 3.4 THz most recently (designated as Antenna C). Our log-periodic antennas have a 4:1 bandwidth. The antenna is fabricated from a gold film using lift-off lithography. At the moment, we use no reflection matching for the silicon lens ($e_r = 11.8$). Optical losses should decrease by about 2 dB once a suitable material for such coatings in the THz range. One such material, which is under investigation, is parylene [11][12].

The HEB receiver is cooled in an IRLAB liquid helium dewar, and THz radiation enters the dewar through a 0.75 mm thick polyethylene window, as shown in FIG.3. The mixer is connected through a bias tee and a semi-rigid coaxial cable to a cooled HEMT IF amplifier. In the most recent experiments, the IF chain noise temperature was estimated to be 7 K with a bandwidth from 1250 MHz to 1750 MHz.

The LO source was a difluoromethane gas laser, which could be made to lase either at 191 µm wavelength (1.56 THz) or at 134 µm (2.24 THz) by choosing one of two orthogonal polarizations. It has an invar-supported structure which was designed with thermal compensation to maintain constant cavity length. In order to obtain high power single mode output, uniform couplers consisting of wire grids deposited on a silicon substrate (also coated for high reflectivity from 9-11 µm) were used. The laser beam was measured to have a Gaussian spatial output profile with the first sidelobes 20 dB down. The FIR laser was pumped by an extremely stable two meter long grating-tuned CO_2-laser. The available power from the CO_2-laser was

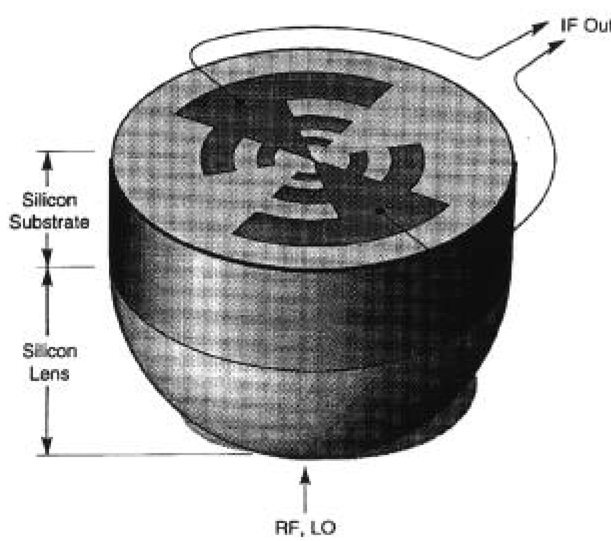

FIG. 2. Log-periodic toothed antenna fabricated on a silicon substrate and attached to a silicon lens.

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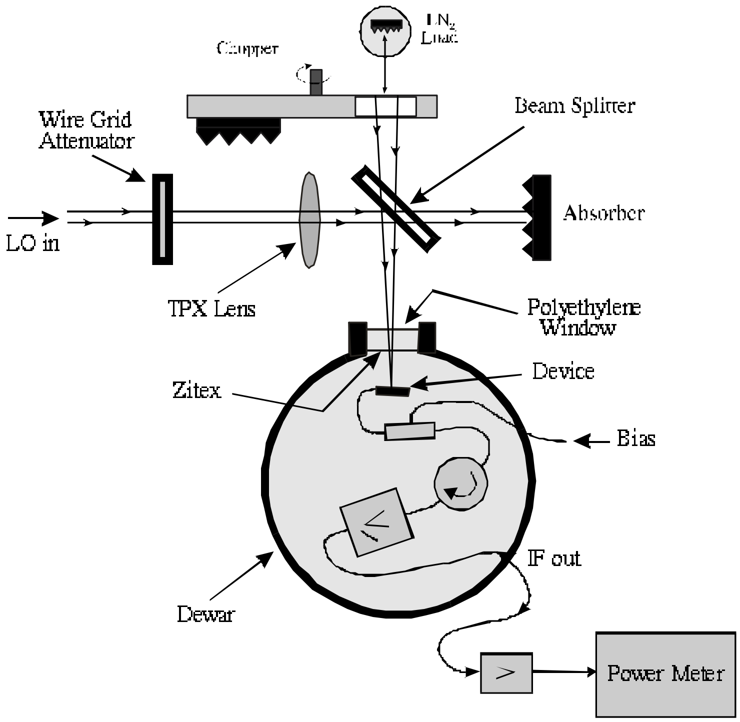

FIG. 3. Measurement setup for noise temperature.

about 200 W [13]. A 6 μm thick mylar window was used as beam splitter. A dielectric lens was used to focus the laser LO. The 50-100 mW output power of the laser was attenuated by crossed wire grid polarizers in order to set the optimum LO level. Although mechanical chopping of the hot/cold source is possible and sometimes used, a typical measurement was performed by inserting a room temperature absorber in front of the LN_2 load by hand. The IF output power was detected on a power meter and recorded in a computer with the help of a *Labview* program. The fact that it is possible to perform the Y-factor measurement without the use of a rotating chopper is a tribute to the excellent amplitude stability of the UMass/Lowell laser used for this experiment. The amplitude stability of the 1.56 THz laser source, measured over a period of minutes, with a relatively fast (0.1 s) integration time, was 0.3%. The stability was also evident in the I-V curves recorded by our fast (about 50 ms) computerized recording system.

III. EXPERIMENTAL RESULTS FOR SINGLE-ELEMENT RECEIVERS

TABLE I gives a summary of data measured for devices which reached DSB noise temperatures at 1.56 THz of 500 K and at 2.24 THz as low as 1,100 K. The output noise temperature was measured by comparing the total output noise power in the optimum operating point (with LO applied) with that of the device in the superconducting state (the bias voltage was decreased to zero). Since the IF noise temperature was

TABLE I. SUMMARY OF NOISE DATA

f [THz]	Dev.# / Ant.	T_{out} [K]	T_{DSB} [K]	$T_{DSB,i}$ [K]	$L_{c,tot}$ [dB]	L_{opt} [dB]	$L_{c,i}$ [dB]
1.56	6/C	110	500	180	9.5	4.5	5.0
2.24	6/C	110	1,100	180	12.9	7.9	5.0

known, we could find the output noise temperature (T_{out}) from this measurement. The optical coupling loss was estimated from known losses in windows, lens reflection loss, etc. The remaining conversion loss is the intrinsic conversion loss, $L_{c,i,}$ which can be calculated from theory according to the standard model. A set of consistent values of $L_{c,i}$, T_{out}, and $T_{R,DSB}$ can then be obtained [8]. We have identified part of the increase (0.5 dB) in optical losses from 1.56 THz to 2.24 THz as being due to a resonance in the polyethylene window material. Also, the atmospheric attenuation is higher at 2.24 THz than at 1.56 THz. The thermal noise power from the cold source had a path length of about 0.6 m before it reached the dewar window and the estimated attenuation over this path at 2.24 THz is 0.5 - 1 dB. There is still an unexplained increase of about 2 dB. Some of the increases in optical losses are inevitable but careful optical design should be able to eliminate a part of this increase with frequency.

IV. FOCAL PLANE ARRAYS WITH INTEGRATED HEB RECEIVERS

In order to fully utilize the future space-borne and airborne facilities, it will be advantageous to develop Focal Plane Arrays (FPAs) which incorporate the new low-noise HEB receivers. In astronomical THz observations, for example, one often wants to map an area such as an interstellar cloud or a galaxy. The speed with which this mapping can be done will increase in proportion to the number of elements in the array. Such systems exist at millimeter waves in ground-based telescopes [14][15]. There are well-known limitations for the smallest beam spacings which can be obtained [16]. These can be discussed in terms of the geometric spacing (Δx) of adjacent elements in the array. If each element in the array illuminates a telescope at an f-number of f/D, then ideal sampling of the focal plane image at the Nyquist rate requires that $\Delta x = 0.5 \times (f\lambda/D)$ [15][17]. There is no type of feed element which is capable of being spaced this close while still illuminating the telescope efficiently [15][18]. About the best which has been achieved in practice is $\Delta x = 1x(f\lambda/D)$, and corrugated horns, for example, which are very efficient feed antennas, must be spaced at about $2x(f\lambda/D)$ [15]. The displacement (N) of the telescope beam on the sky, measured in Full Width Half Maximum Power (FWHM) beamwidths is also related to Δx by $N \approx \Delta x/1.2\lambda(f/D)$ [16]. An array element spacing of about $1.2x(f\lambda/D)$ thus corresponds to a spacing of adjacent beams on the sky of one FWHM beamwidh.

There are two different methods for coupling dielectric lenses to an antenna array:
(*i*) a single-lens configuration; and
(*ii*) a multi-lens configuration.

If we first consider the single-lens case, the individual elements placed near the focus of the lens will radiate a beam which has an f-number of roughly 1.0, i.e. a 56 degree FWHM beam width. Filipovic et al. [19] analyzed this case and derived the minimum spacing possible. To obtain a rough estimate, we assume a spacing corresponding to one beam width, and find $\Delta x \approx \lambda_0 / \sqrt{\varepsilon_r}$, or 35 µm for $\lambda_0 = 119$ µm. This leads to very tight constraints on any wiring which has to be connected to the devices and antennas, and it is obviously impossible to place the IF amplifiers close to the antennas.

The multi-lens configuration, on the other hand, is much more flexible. The relatively small (radius $R \approx 10\,\lambda_0$) elliptical lens which we have developed, lends itself well for use in this "fly's eye" type of array, see FIG. 4. Both the LO and the incoming signal are injected through a quasi-optical diplexer. The optics thus are unchanged from our single-element approach. The beam width from each lens is approximately given by 1.2 x $\lambda/(2R)$, and the lenses can be placed at a spacing equal to their diameter (2R), i.e. $\Delta x = 2R$. The f-number of the array elements will be approximately $2R/\lambda$ ($\approx$ 20), which may be about right for a typical Cassegrain telescope, without recourse to further focusing. The beam-scan (N) will be about one FWHM beam width. The angular resolution (angular spacing between adjacent pixels) will thus be about equal to the diffraction-limited beam width of the telescope, which is typical of the best resolution obtainable for FPA receivers as discussed above.

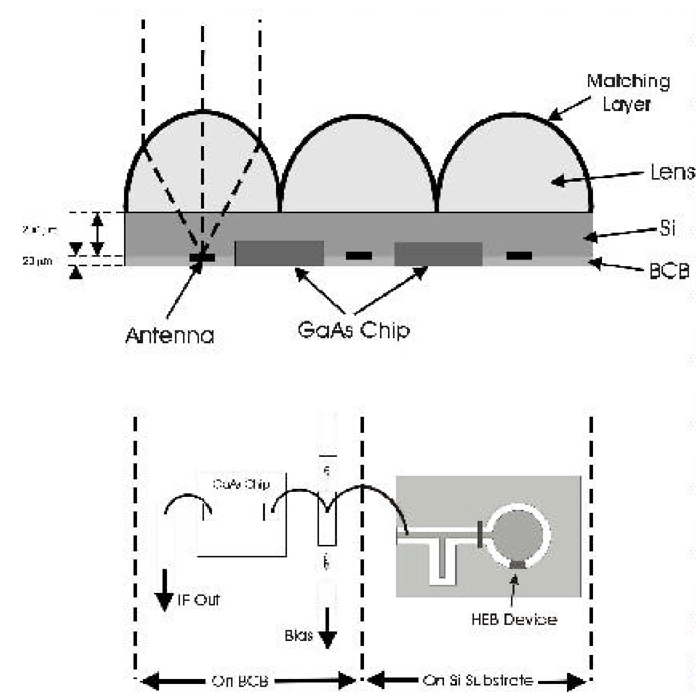

FIG 4. A portion of an HEB THz focal plane array.

The FPA can not use the log-periodic toothed antennas which we have employed so far since these are un-necessarily large. The focal plane array system is also not likely to require the very wide bandwidth of these antennas. We instead propose a slot-ring antenna as shown in FIG. 5 (a double-slot antenna would also be possible). The slot-ring antenna has been demonstrated in a four-element array for a 35 GHz monopulse radar [20] and also, for example, in 94 GHz MMIC receivers [21]. This antenna is linearly polarized and can receive radiation in either of two perpendicular polarizations. There are several possible configurations to explore. FIG. 5 shows one such configuration in which the LO and RF are injected in the same polarization as in our present single lens receiver. The IF is extracted through a coplanar waveguide (CPW) from the point on the ring at which the THz fields have a null. It is important to use air bridges in order to cancel the even mode on the CPW. In the above-mentioned monopulse radar project, the LO and signal were injected in opposite polarizations through a simple wire grid and two (reversed) Schottky barrier mixer diodes were placed at the 45 degree positions across the ring thus forming a balanced mixer. HEB devices can not be reversed, as can Schottky diodes, but one or two devices could be placed at the 45 degree positions and this would allow very efficient LO injection (ideally without any loss) through a wire grid. The signal would also be injected without loss, ideally. The RF impedance of the HEB device(s) would be adjusted in the usual way by varying its (their) aspect ratio for optimum coupling to the ring. Different types of filters can be tried on the IF line in order to prevent leakage of the RF and LO through the CPW. FIG. 5 and FIG. 6 show different versions of this.

The entire silicon chip with antennas and NbN mixer devices would be fabricated in one process. MMIC HEMT amplifier chips (size about 1 mm^2) would be integrated with the mixers by inserting them in etched wells in the silicon substrate, and transmission lines could be routed on a thin layer of spun-on dielectric. FIG. 7 shows a wideband MMIC amplifier under development in collaboration with Chalmers University of Technology [courtesy of Herbert Zirath]. The amplifier will include (on chip) the appropriate impedance transformation as well as bias circuitry for the HEB devices. A nominal bandwidth of 4-8 GHz will be suitable for

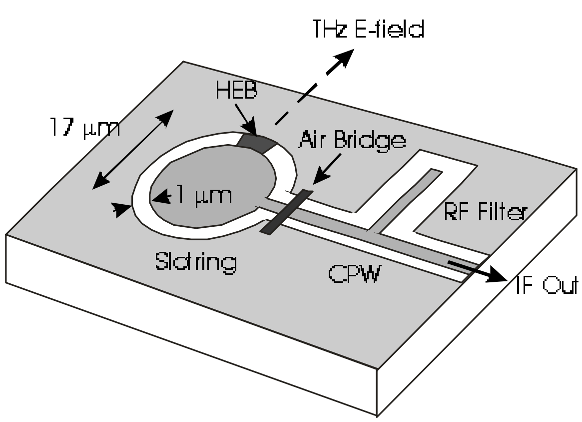

FIG 5. HEB device coupled to a slot ring antenna with coplanar waveguide output for the IF.

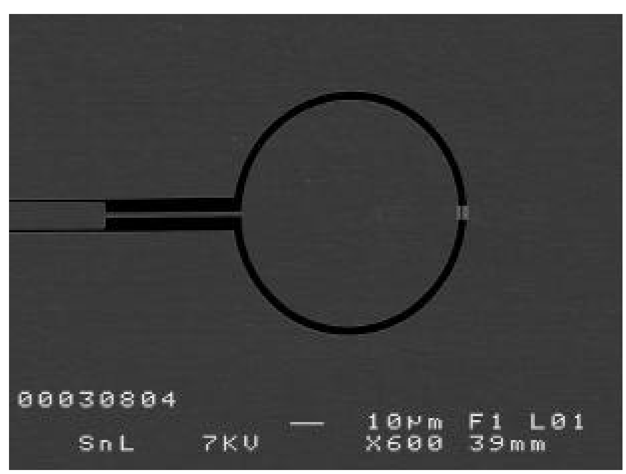

FIG 6. A different version of the slot ring antenna/HEB device.

many anticipated system applications. Another important consideration is to minimize the DC power consumption of the MMIC amplifier.

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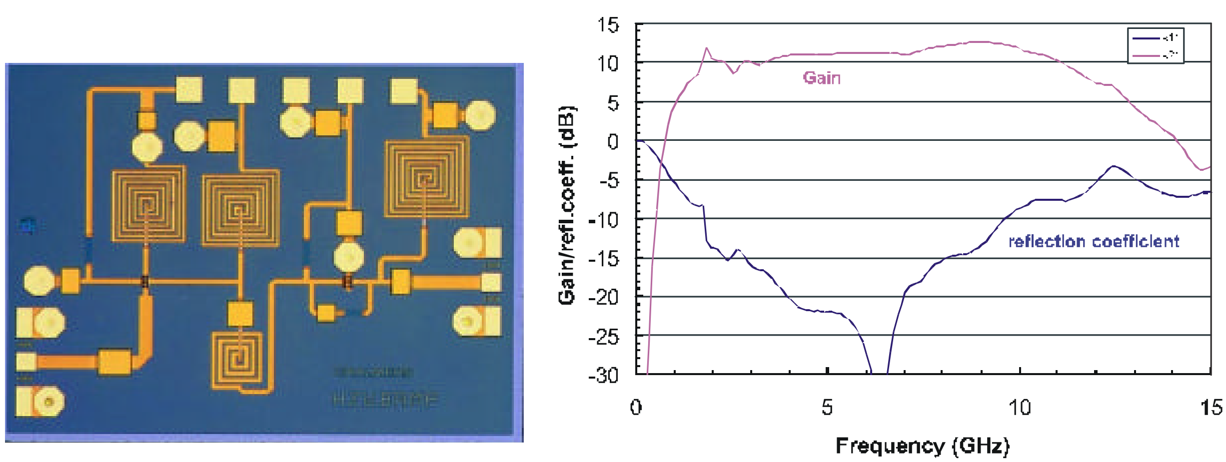

FIG 7. Wideband (2-12 GHz) MMIC PHEMT amplifier designed at Chalmers University. Measured data for gain and reflection coefficient are also shown.

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