Investigation of a thermoelectrically cooled UHF radar amplifier module

MIT HAYSTACK OBSERVATORY

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Michael Shusta
University of Massachusetts-Amherst
Advisors: Frank Lind and Jim Marchese

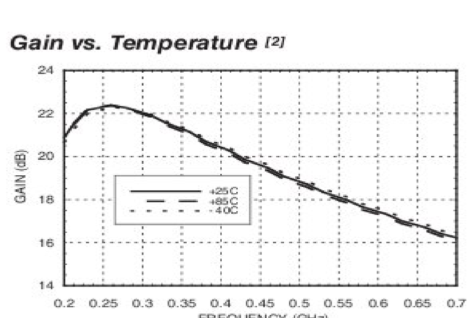
Abstract

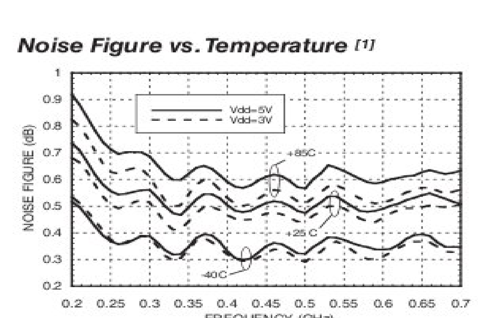
In radio instrumentation, the system noise level of a receiver is dominated by the noise added by the first stage after the antenna: the low-noise amplifier (LNA) . It sets the performance of the receiver in terms of gain, noise figure, stability, and dynamic range. Radar operators working in astronomy and atmospheric science who desire very low system temperatures cool their front-end LNA with cryogenic apparatus. The primary motivation of this engineering project is to achieve a more modest performance gain with simpler, cheaper, and lower-maintenance means: thermoelectric cooling. Thermal simulations of a UHF front end module were performed in the COMSOL Multiphysics environment, which show LNA cooling to 200K. A vacuum housing design and thermal analysis are shown, to be implemented in the Millstone Hill Incoherent Scatter Radar at MIT Haystack Observatory.

Motivation

Maintenance: In the case of the Millstone Hill Incoherent Scatter Radar, the ionosphere is probed with peak transmit power of 93 to 96 dBm, with 40 dB of isolation provided by a turnstile junction and transmit/receive (T/R) switch. A typical LNA at the beginning of the receiver stage handles roughly 20 to 30 dBm of input power. If the T/R switch fires out of sync or not at all, the receiver will be broken. Lightning strikes may also burn out the front end.

Performance Gain: The temperature dependence of noise figure is well known: the degradation of signal-to-noise ratio from a component is minimized by lowering the temperature of the device. In the case of the LNA used in the preliminary design of this project, the Hittite HMC616LP3, the following graphs illustrate this point:





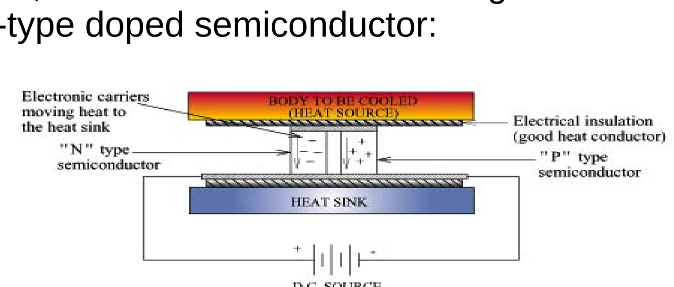
This performance gain is critical in the receiver front end because the cascaded noise figure of any system is effectively set by the gain and noise figure of the first stage[1]:

$$F_{cas}=F_1+\frac{(F_2-1)}{G_1}+\frac{(F_3-1)}{(G_1 \cdot G_2)}+...$$

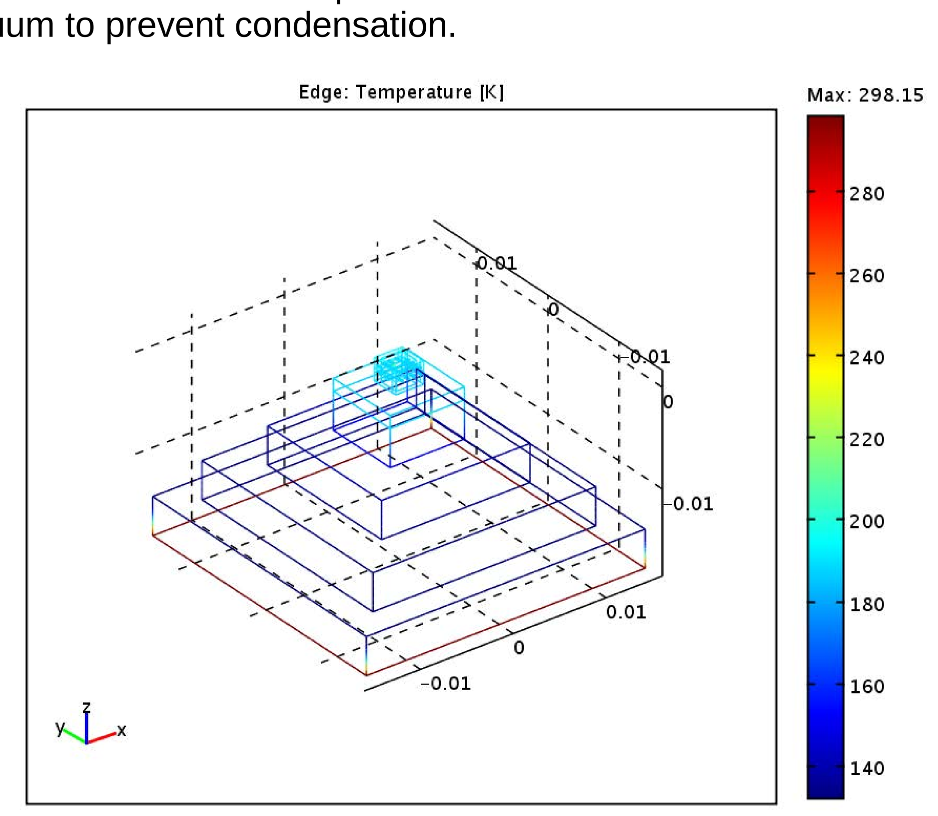
By choosing a first stage LNA with low noise figure and high gain, the best possible performance upon thermoelectric cooling is achieved. The Hittite HMC616LP3 and RFMD SPF-5122Z were used in separate design phases.

Thermoelectric Cooling

How It Works: A thermoelectric cooler (TEC) is a semiconductor device which exploits a physical phenomenon called the Peltier effect: when current passes through two differing conductors, a temperature difference occurs while heat it pumped. In today's TEC devices, a direct current is fed through a set of alternating n-type and p-type doped semiconductor:



How It Was Used: The heat-sink on the underside of the LNA chip is placed in thermal contact with the cold face of a layered TEC pyramid. A separate TEC stack stabilizes the surrounding printed circuit board (PCB). The thermoelectric coolers chosen for this project sustain a temperature differential of 110K while pumping 200mW of heat. This implies that the front-end must sit inside a vacuum to prevent condensation.



TEC Stack Cooling an Integrated Circuit

Design Considerations

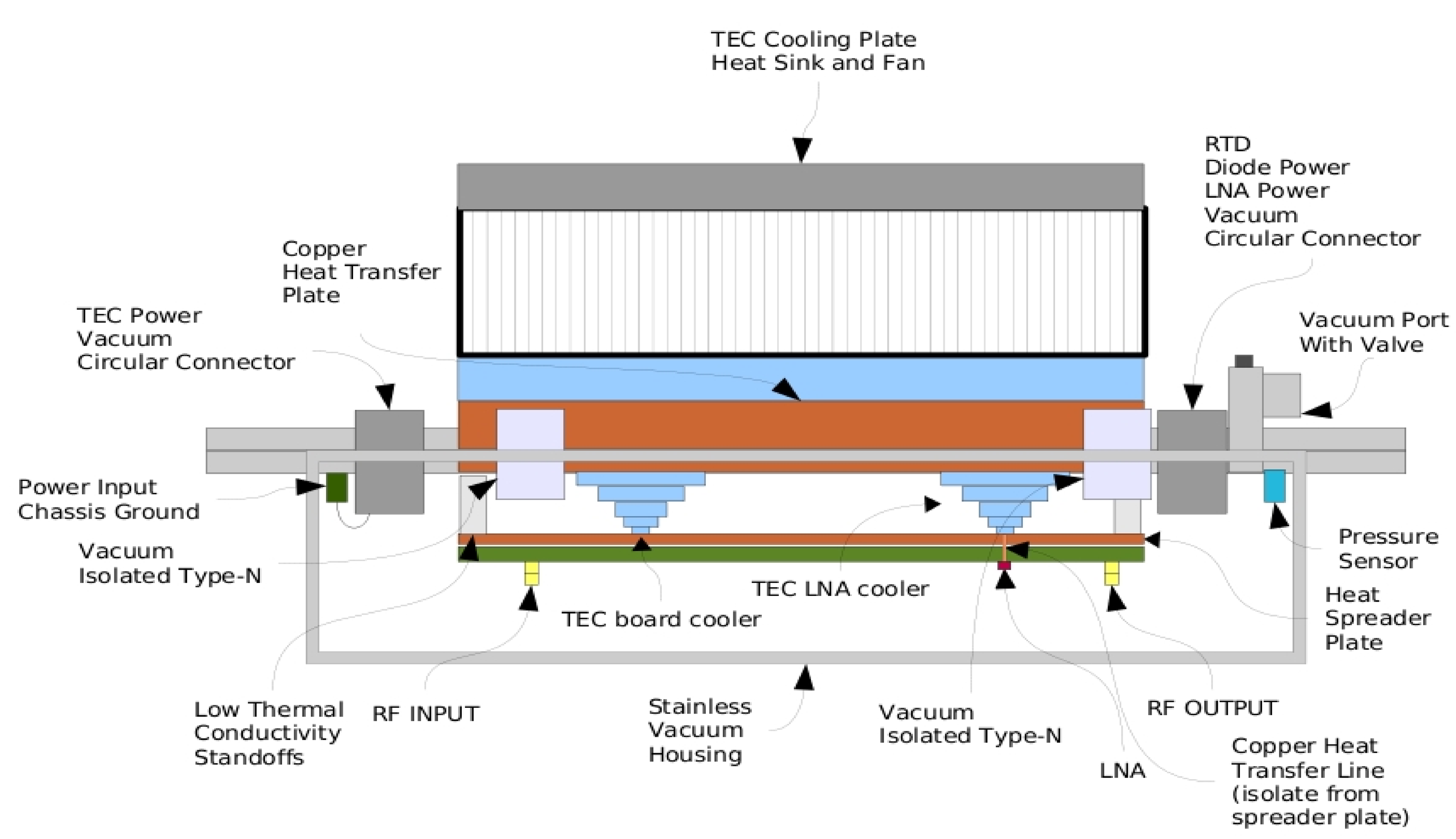
Mechanical Layout: The RF board and vacuum design are shown below: the thermoelectric cooler stacks sit between two copper plates with through-holes for mounting the PCB. There is a cutout underneath the LNA's heat-sink where plastic-coated copper wire is used to conduct heat directly to the TEC beneath it and isolate it as much as possible thermally from the rest of the PCB. The mounting structure above the copper block and flange is easily removable for maintenance.

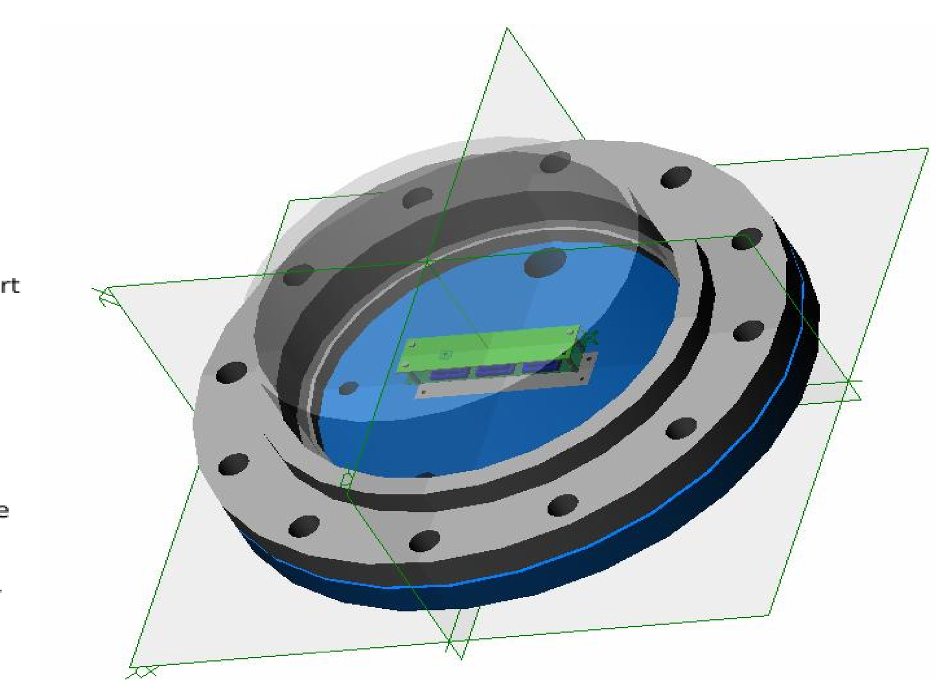
Thermal Analysis: An upper bound on total heat generated by the receiver front end was computed. The total heat includes conduction from the temperature gradient created by the TEC, radiation from the housing, and ohmic dissipation from power supplied to the components and TECs themselves:

$$Q_{cond}=\lambda(T)\cdot A\cdot\frac{dT}{dx} \qquad Q_{rad}=\epsilon\cdot\sigma\cdot A\cdot T^4 \qquad Q_{ohmic}=V\cdot I$$

Evaluating these equations leads to 425.1mW conducted into the board. 1.79 Watts radiates into the PCB. Metal-coated mylar, which reflects radiant heat, is used to negate this. Ohmic dissipation through the coolers and components puts the total heat exhausted from the vacuum chamber at 50W. Only 100mW of this heat is generated by the LNA. The TEC stack can sustain this, while the rest of the heat must be exhausted: a cold plate with integrated fan, was chosen to couple with the copper mount externally.

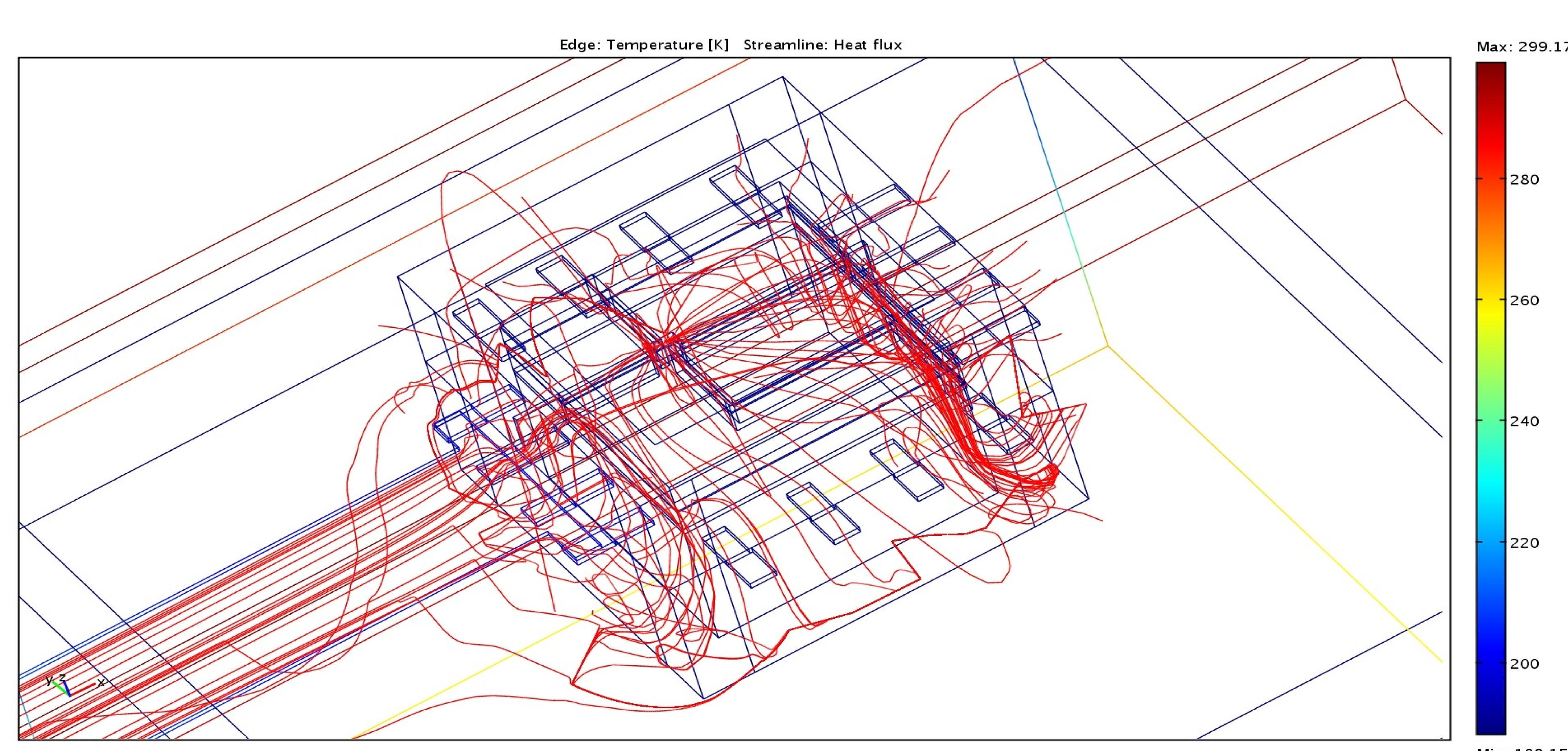
Conceptual Drawing and CAD Model of Vacuum Design

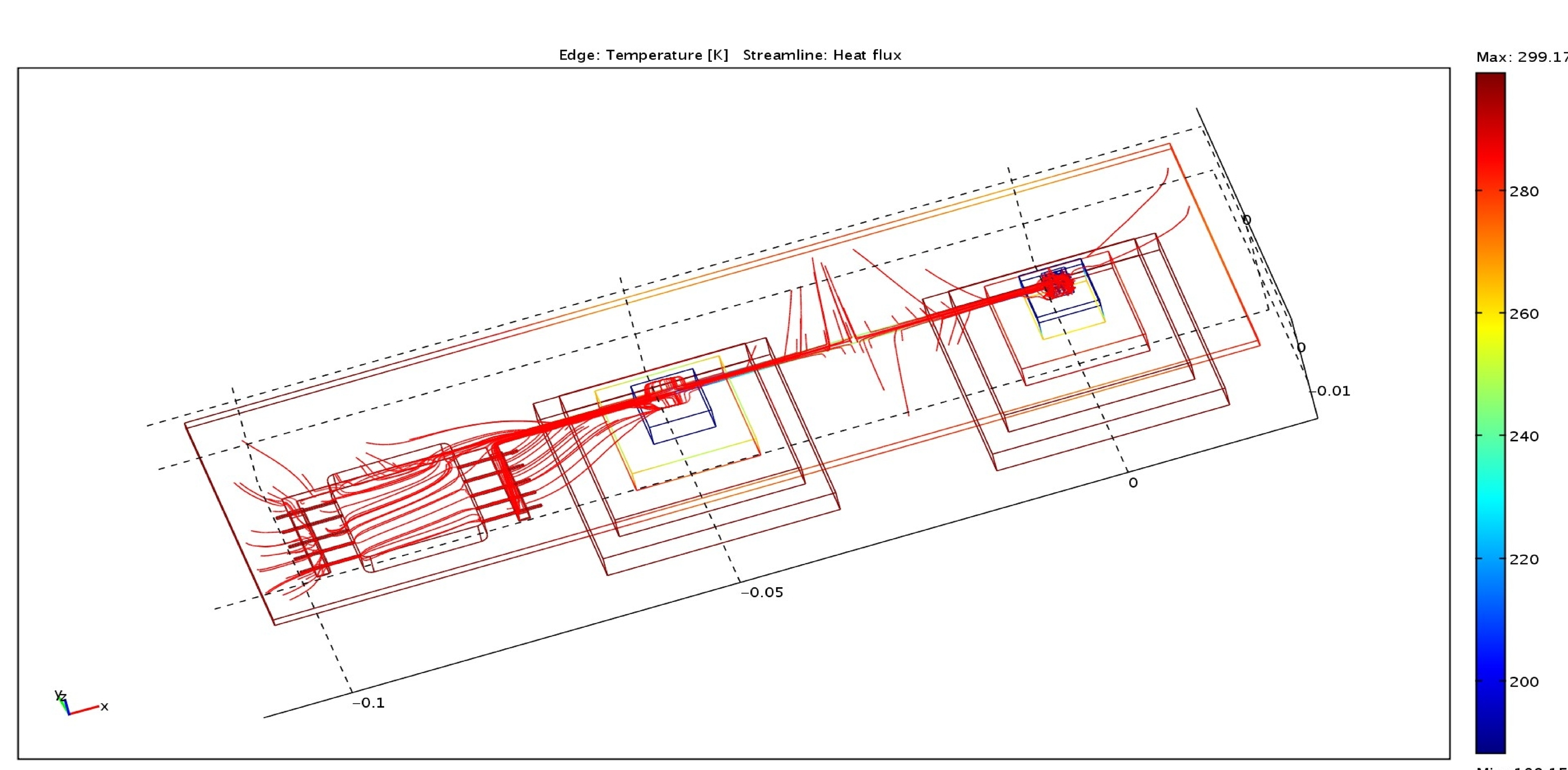




Multiphysics Simulation

COMSOL Multiphysics simulation was used to guide the design process. It was shown that the DIP-packaged LNA chip in the design could be cooled to 200K with a thermoelectric stack. Previous investigation of TEC-cooled LNAs by engineers from the Square Kilometer Array show positive results, but a bare die was used[2]. The Hittite HMC616LP3 LNA in this design was modeled down to the layers of semiconductor and put in a coupled environment in which the TEC stack, noise diode and PCB played a realistic role. Simulations confirm that heat generated by the LNA flows to the TEC while surrounding heat sources do not interfere significantly with the LNA due to the geometry of the board. Steady-state COMSOL simulation results are seen at below as edge temperatures and heat flux lines.





Simulation Results:

·100mW heat source inside LNA is cooled to 200K

·Translates roughly to 0.4dB drop in noise figure to 0.2dB

·Metal lines sustain largest heat flux

·PCB does not sit at uniform temperature (heat conduction/control system implications)

·Noise diode heat is mostly absorbed by center TEC

Conclusion

The motivation, simulation, and design of a thermoelectrically cooled front end module for a UHF radar system was presented. Low-noise amplifier cooling to 200K with this approach was shown. A mechanical design and thermal analysis was provided for fabrication and implementation of two chambers in the Millstone Hill Incoherent Scatter Radar at MIT Haystack Observatory.

References: [1] D. M. Pozar, *Microwave Engineering*, 2nd Edition. New York, NY: Wiley & Sons, 548-559. [2] Schreuder, Bij de Vaate, "*Localized LNA Cooling in Vacuum,*" THERMINIC Workshop 2006.