SUPERCONDUCTING HOT-ELECTRON BOLOMETER MIXER FOR TERAHERTZ HETERODYNE RECEIVERS

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A number of on-going astronomical and atmospheric research programs are aimed to the Terahertz (THz) spectral region. At frequencies above about 1.4 THz heterodyne receivers planned for these missions will use superconducting hot-electron bolometers as a mixers. We present recent results of the terahertz antenna development of superconducting NbN hot-electron bolometer mixer for GREAT (German Receiver for Astronomy at Terahertz Frequencies, to be used aboard of SOFIA) and TELIS (Terahertz Limb Sounder). The mixer is incorporated into hybrid antenna consisting of a planar feed antenna, which has either logarithmic spiral or double-slot configuration, and hyper hemispherical silicon lens. The hybrid antenna showed almost frequency independent and symmetric radiation pattern with the beam-width slightly broader than expected for diffraction limited antenna. The noise temperature as well as its spectral dependence changes with the bolometer sizes that provides additional tool for mixer optimization. FTS spectra measured in the direct detection regime agreed with the noise temperature spectra.

Mixer and Antenna Design

Hot-electron bolometers (HEBs) were manufactured from a superconducting NbN film with a nominal thickness of about 3 nm. The film was deposited by dc reactive magnetron sputtering on a 350-μm thick Si substrate. The HEB was incorporated in a planar feed antenna patterned from a 200 nm thick gold film. The bolometer had an area of one tenth of a square, i.e. the width amounted ten times the length. Given the normal sheet resistance ≈ 600 Ohm at the transition temperature of the NbN film, the resistance of the bolometer just above the superconducting transition should be 60±6 Ohm as determined by the accuracy of the manufacturing process. However, the contact resistance between the HEB and the inner terminals of the antenna affected the actual device resistance. The contact resistance varied depending on the contact area and contact quality. Two types of feed antenna have been studied: self-complementary logarithmic-spiral and twin-slot. We tested three logarithmic-spiral antennas with different sizes of the inner terminals and double-slot antennas optimized for several frequencies in the range from 1.5 THz to 3 THz. Antenna parameters are depicted in Fig.1 and specified in the Table. The substrate carrying the HEB and the feed was glued with its backside onto the flat optically polished side of an extended hemispherical 12 mm diameter silicon lens. The 3.5 mm extension of the lens together with the substrate thickness positioned the feed in the second elliptical focus [1]. The lens had a Parylene antireflection coating optimized for 2.5 THz [2]. The lens with the HEB was mounted in an Infrared Labs helium dewar with a wedged TPX vacuum window and a cold (77 K) quartz filter.

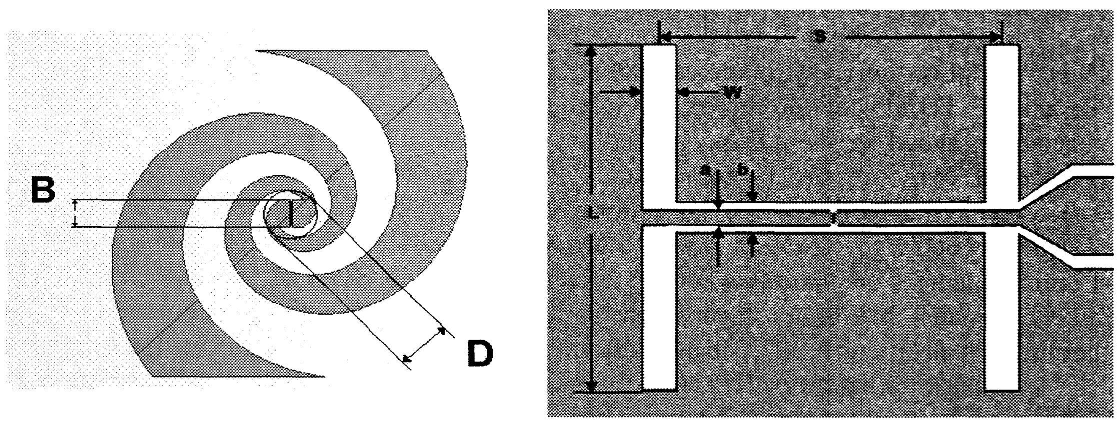

Fig. 1 Planar log-spiral (left) and twin-slot (right) antennas. Gold is shown gray. Black rectangle in the geometric center of the antenna depicts the bolometer. For log-spiral feeds: D is the diameter of the circle that demarcates the spiral structure of the feed from the contact pad area; B is the largest bolometer width that the feed may have embedded.

Table. Sizes in micrometers of studied log-spiral and twin-slot planar feeds.

Log-spiral feed		
Antenna type	B	D
Sp_a	4	14
Sp_b	2.4	8
Sp_c	1.5	3.5

Twin-slot feed					
Antenna type	L	S	W	a	b
TW1	62	32	4	2	4
TW2	40	21	2.2	2.2	3.3
TW3	33.6	20	2.6	2	4
TW4	46	24	3	2.2	3.3
TW5	33.6	17.5	2.4	2	3

Experimental arrangement

The intermediate frequency (IF) signal was guided out of the mixer via the 50-Ω coplanar line. A circulator was used to feed the bias to the mixer and to transmit the IF signal to a low noise HEMT amplifier, which had either 1 – 2 GHz or 4 – 8 GHz bandwidth. The IF signal was filtered by an electrically tunable filter with a bandwidth of 75 MHz, further amplified and rectified with a microwave crystal detector. An optically pumped FIR laser providing lines at frequencies 0.69, 1.63, 2.53, 3,1 and 4,2 THz was used as a local oscillator (LO). Signal radiation and LO radiation were superimposed by a 6 μm thick Mylar beam splitter. The double sideband (DSB) noise temperature of the receiver was measured by the Y-factor method. Hot and cold loads (Eccosorb) at 293 K and 77 K alternatively covered the receiver beam. Output signal, that is the dc voltage at the crystal detector, was continuously readout by a computer, which performed statistical analysis of the signal and computed the noise temperature. The beam pattern of the hybrid antenna was measured at two LO frequencies, 1.6 THz and 2.5 THz, by moving a hot, point-like source in the far field of the receiver. The output heterodyne signal was registered as a function of the position of the source. FTS measurements were performed in the direct detection regime with the mixer kept at the middle of the superconducting transition. We used a simple cube interferometer with a 12-mm thick Mylar beam splitter and a mercury discharge lamp as radiation source. The mirror was moved with a step motor. Typically, ten or more computed spectra were accumulated and averaged in order to increase the sensitivity.

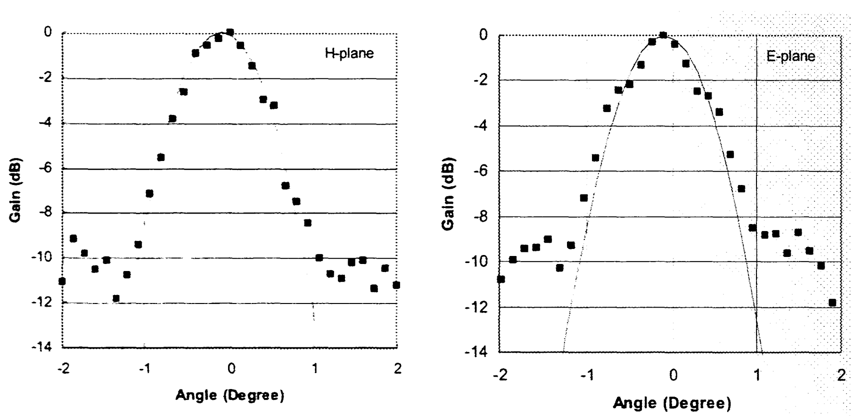

Fig. 2. Beam profile of the twin-slot antenna TW2 at 1.6 THz in the H- (left panel) and E- (right panel) planes. Solid lines show the Gaussian fit with the 3-dB width of 1.1°.

Antenna beam pattern

At 1.6 THz we found for the twin-slot feed antenna a 3-dB beam width of 1.1° in both E- and H-planes. The pattern was fairly symmetric (Fig. 2) with the side lobes appearing slightly below –10 dB. The log-spiral feed had at this frequency the same side lobe level and also showed symmetric beam pattern (Fig. 4). The polarization of the antenna was elliptical with the middle value 1.3° of the 3-dB beam width. There was a 15% difference between the beam width in two main elliptical planes, indicating that at this frequency the twin-slot feed is probably the better choice than logarithmic-spiral. However, this changes at higher frequencies where the required dimensions of the twin-slot antenna become comparable to the size of the IF embedding circuitry. This brings parasitic impedances and destroys coupling [3] between the feed and the embedding circuitry.

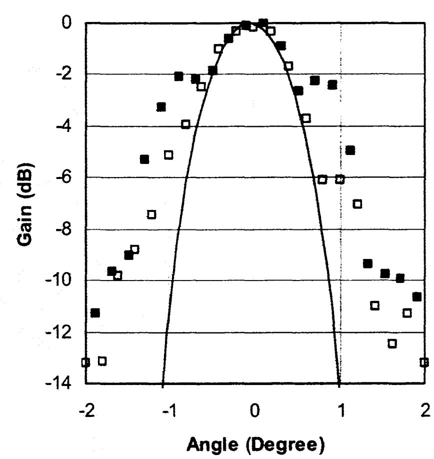

Fig. 3. Beam profile of the twin-slot antenna TW3 at 2.5 THz in the H-plane (filled symbols) and in the E-plane (open symbols). Solid line presents the Gaussian fit to the main lobe with the 1.5° beam width at –3 dB.

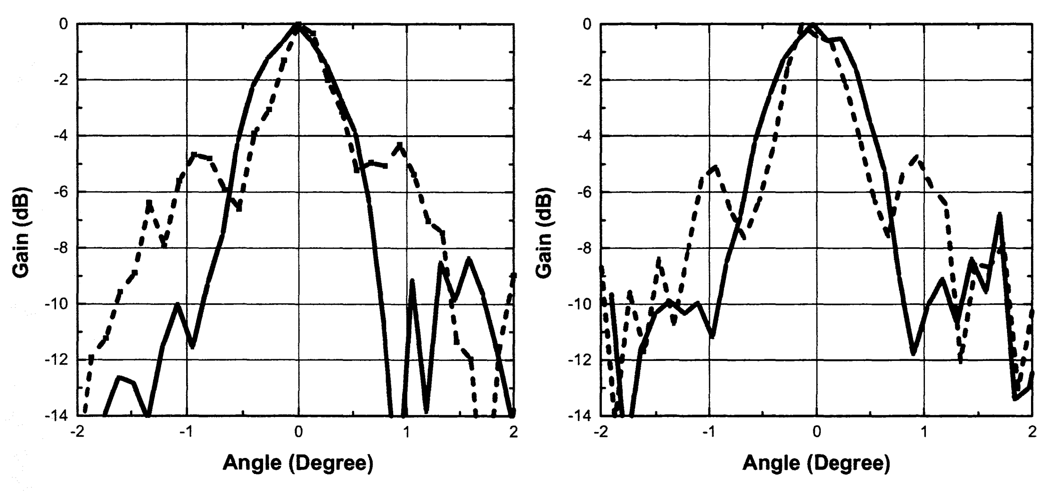

Fig. 4. Beam profile of the log-spiral antenna Sp_b at 1.6 THz (solid line) and 2.5 THz (dotted line) in main elliptical planes.

At 2.5 THz, we found (Fig. 3) higher side lobes (-3 dB) and wider beam pattern (1.5°) for the twin-slot feed. The log-spiral feed had at this frequency (Fig. 4) an almost symmetric circular polarized beam with a 3-dB width of 0.8° and side-lobes at –5 dB.

Spectral properties: Noise temperature

Generally, the noise temperature of a HEB mixer imbedded in the planar feed increases with frequency. That might be a manifestation of the detection mechanism [1] as well as the electrodynamics of the feed or optical coupling. We made an attempt to separate the contribution of the feed and the HEB geometry in that we measured the noise temperature as function of frequency for several identical feeds having bolometers with different planar dimensions. The length and the width of the bolometer were both changed proportionally in order to keep the number of squares and the impedance of the bolometer unchanged. Data shown in Fig. 5 suggest that the noise temperature grows faster for bolometers with larger width. This result seems to be a natural consequence of the skin effect in the bolometer. Indeed, the skin depth in our NbN films [1] is ≈ 0.57 μm at 2.5 THz that is noticeably smaller than the bolometer width.

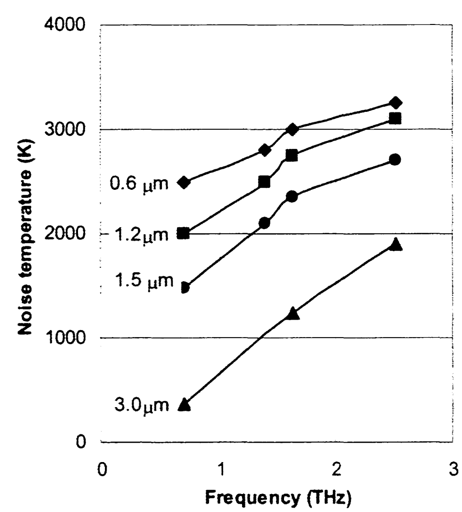

Fig. 5 Noise temperature for several bolometers with different width (shown in the plot) embedded in the log-spiral feed of the type Sp_a.

Although the noise temperature at a particular frequency tends to increase when the bolometer width decreases, this trend can be hardly treated numerically. Because of a very large spread of the noise temperatures between batches of identical mixers, the error bar would be larger than the expected variations. The reason for that is most likely poorly controllable contact resistance between the bolometer and the inner terminals of the feed. The best noise temperatures at 2.53 THz (1.5 GHz intermediate frequency) were 1600 K for Sp_a with 3 mm bolometer width, 2200 K for Sp_b with 1.3 mm bolometer width. and 2600 K for Sp_c with 1.5 mm bolometer width. We shall note here that the power of the local oscillator required for optimal (lowest noise temperature) operation increases in proportion to the bolometer volume. We have directly measured the 2.5 μW LO power in front of the cryostat window at the optimal operation of a 1.6-μm wide bolometer imbedded in the Sp_b feed. Expected power for a 3-μm wide bolometer is four times larger that might be crucial for applications relying on solid state LO sources.

The frequency dependence of the noise temperature for log-spiral feeds Sp_a and Sp_c is shown in Fig. 6. Typically, the feed Sp_a, which is capable to carry a larger bolometer, shows smaller noise temperature at any particular frequency. In order to compare electrodynamics of feeds and possibly avoid the effect of contact resistance, we used two different feeds with identical bolometers having the dimensions 1.5 x 0.15 μm^2. The feed Sp_c with the spiral structure going down to a smaller radius (see Fig. 1 and Table) better performs at higher frequencies. According to [4], the upper cut-off frequency of a log-spiral feed should be (c is the speed of light and ε is the dielectric constant of the substrate)

$$\nu_0 = \frac{c}{5D\sqrt{(1+\varepsilon)/2}} \tag{1}$$

For our Sp_a feed antenna $\nu_0 \approx 1.6$ THz that agrees within the accuracy of the cut-off definition with the data presented in Fig. 6. Following the same criteria, one should expect for Sp_c the cut-of at 6 THz.

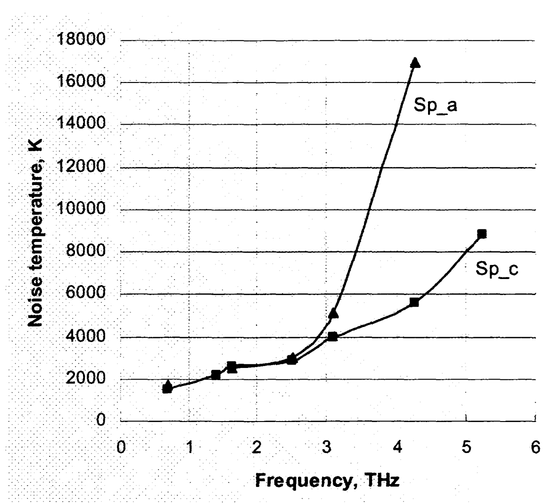

Fig. 6 Noise temperature of the log-spiral feeds Sp_a (triangles) and Sp_c (squares) with identical bolometers.

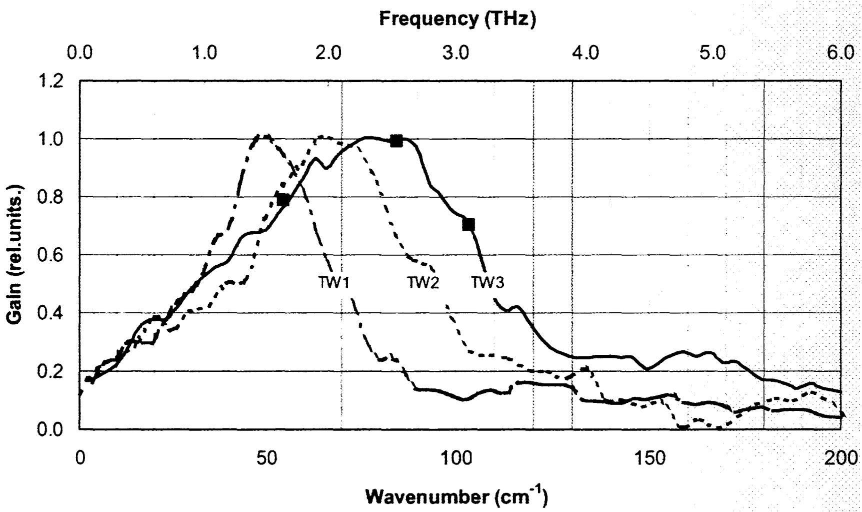

Fig. 7. Normalized to maximum FTS spectra of three twin-slot feeds. Dimensions are presented in the Table. Black squares show normalized noise temperature measured with the same TW3 feed.

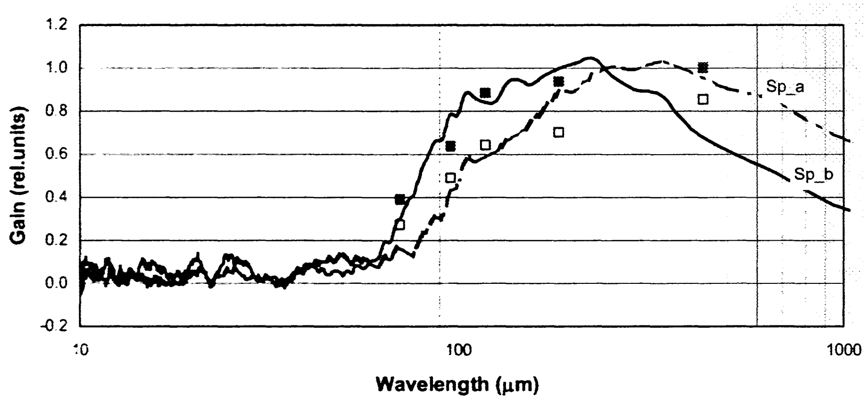

Fig. 8. Normalized to maximum FTS spectra of two log-spiral feeds (solid line Sp_b, dotted line Sp_a) and measured noise temperatures (closed symbols Sp_b, open symbols Sp_a).

Spectral properties: Fourier transform spectroscopy

FTS spectra of few twin-slot feeds are shown in Fig. 7. For all three, noise temperatures measured at available LO frequencies correspond well to the obtained FTS spectra. Black squares illustrate that for the TW3 feed. Our data shows, in agreement with [3], that the common design rule [5] $L = 1.95 \cdot S$ and $L = 0.33 \cdot \lambda_0$ does not properly work at frequencies above 2 THz. In order to realize the required resonance frequency, the slot length and separation should decrease in excess to the wavelength.

Fig. 8 shows FTS spectra of log-spiral feeds. For this antenna type we also found reasonably good agreement between spectra and measured noise temperature. There is although a contradiction with common understanding of how the cut-off frequency should vary with the feed size. According to (1), the ratio of the smallest spiral diameters D (see Fig. 1 and the Table) dictates the cut-off frequency of the Sp_b almost twice as large as the cut-off frequency of the Sp_a. In fact we have found much smaller increase of the cut-off frequency.

In conclusion, we have studied spectral properties and beam pattern of log-spiral and twin-slot feeds at terahertz frequencies and found feed sizes resulting in reasonably good performance. Comparison of two types of fed antenna suggests that at frequencies above 2 THz the spiral feed, although it has not very practical elliptical polarization, provides better overall performance.

Acknowledgement

The work was partly supported by INTAS, K.S. acknowledges support through personal grant YSF 2002-408 by INTAS.

References

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