Tolerance Analysis of THz-Range Lens-Antenna and Balanced SIS Mixers

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Abstract—**Effects caused by imperfection of extended hemispherical immersion lens-antenna are studied numerically at 865 GHz. Elliptical and aplanatic focusing regimes are tested in combination with double-slot and double-dipole feeds for their aperture efficiency in the presence of multiple misalignment factors, which include possible phase and amplitude asymmetry of complimentary SIS tuning circuit. A new balanced lens-antenna SIS mixer is analyzed for its aperture efficiency with respect to an IF bandwidth of 4-12 GHz. Experimental data on lens-antenna SIS mixers with epitaxial NbN-AlN-NbN tunnel junctions is presented.**

Index Terms—**lens-antenna, aperture efficiency, quasioptical mixer, SIS mixer, balanced mixer, NbN tunnel junction**

I. INTRODUCTION

The primary cases to use the immersion lens-antenna are as following: i) a large-chip integrated circuit containing a printed antenna (ex. [1], [2]); ii) a densely packed array of printed antennas (imaging array) fabricated on the same chip (ex. [3]) or iii) need for a very broadband (multi-octave) reception that is not possible with waveguides. The low-noise performance of a lens-antenna THz-band mixer employing SIS junctions has been demonstrated quite some time ago [4], [5]. The most attractive feature of the lens-antenna technology is that the size of quasioptical chips is not dependent on frequency; the chips are easier to process and can be handled with much less caution. Numerical models are often based on perfect symmetry of the structure and accuracy of its parameters. However, this cannot be always achieved at submillimeter wavelength. The accuracy of mechanical (optical) parts and their alignment are limited usually by a few micrometers. The misalignment of the lithography process is typically up to half-micron. The required accuracy of SIS junction size must be often better than 50 nm. This list does not include yet some random defects of the structure and slight changes in properties of sputtered materials, which are difficult to detect. Since we are aiming the option development of balanced/quasioptical mixers for ALMA Band-10 (787-950 GHz), many precise components are used, and the tolerance analysis is of great interest for understanding possible restriction on design/performance of our mixers. This report is focused on analysis of the following specific problems of the symmetry-based SIS mixers:

- Beam distortion of a lens-antenna mixer due to positioning error of the antenna with respect to the immersion lens.
- Beam distortion due to amplitude and phase errors caused by photolithography misalignment.
- Beam distortion due to unequal size and impedance of two junctions of a twin-SIS mixer and/or due to inequality of two twin-mixers of a balanced lens-antenna mixer.
- Beam tilt due to unequal phase of two IF output signals of a balanced QO mixer.

The feasibility of the research is not limited to the single-element mixer; its results (and methods) can be applied to a single-lens imaging array for analysis of its off-axis pixels.

II. CALCULATION METHOD AND CRITERIA

The beam has been calculated using a technique of well-known Kirhoff-Hugens' diffraction integral taken over the curved surface of the lens. We have analyzed two cases of focusing of a spherical lens-antenna: elliptical (synthesized) and aplanatic. The printed (lithographic) double-slot antenna and the double-dipole antenna with back-reflector were tested as feeds of the lenses. First we calculated amplitude and phase at two vibrators of a double-element antenna. The far-field beam of the antennas was then calculated assuming a sinusoidal current distribution along the antenna vibrators. The refracting surface of a silicon lens was assumed laying in the far-field. The matching (anti-reflection) coating is attached to the lens surface. No effects of internal reflection are taken into account. The tolerance margins were set as follows: i) off-axis misalignment of antenna (X- or Y-offset) up to 10 μm; ii) on-axis offset (Z-offset) up to 20 mm; iii) lithographic masks offset up to 1 μm; iv) difference in R_n for twin-SIS up to 20% in

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Manuscript received April 30, 2007. This work was supported in parts by the ALMA-J Office, National Astronomical Observatory of Japan, and by ISTC project #2626.

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mixer configurations as in [4], [5]; v) off-axis position of the anti-reflection coating up to 10 μm. As the result the excitation power ratio of two antennas up to 2.3 and phase shift up to 15 degrees are used.

To compare different combinations of lenses and antennas, we used the following well-known integral criteria [6]: the spillover efficiency

$$\varepsilon_s = \frac{\int\limits_{\Omega_0} |E|^2 \cdot d\Omega}{\int\limits_{4\pi} |E|^2 \cdot d\Omega}, \tag{1}$$

(Ω_0 is the solid angle of sub-reflector) and the taper efficiency

$$\varepsilon_t = \frac{\left|\int\limits_{\Omega_0} E \cdot d\Omega\right|^2}{\int\limits_{\Omega_0} |E|^2 d\Omega \cdot \int\limits_{\Omega_0} d\Omega} \tag{2}$$

yielding the full aperture efficiency as

$$\varepsilon_{ap} = \varepsilon_s \cdot \varepsilon_t\,. \tag{3}$$

III. TWO-ELEMENT FEED IN APLANATIC AND ELLIPTICAL FOCUS

The beam and phase patterns of a spherical lens in elliptical regime of focusing shown in Fig. 1(a) and Fig. 1(b) are in reasonable agreement with [7], [8]. The Gaussian impurity of the beam (sidelobes at -18…-20 dB) can be a serious problem within an optical system with numerous limiting apertures. Fortunately, there is no need in intervening optics between the mixer and the sub-reflector of the ALMA telescope, if such lens-antenna is used. Since the Gaussian fit of the nominal beam is good down to the edge of the sub-reflector at -10 dB (Fig. 1a), the beam of the telescope will be essentially the same as the sub-reflector were illuminated with a corrugated horn antenna. Note that the joint result of all misalignments is rather similar to tilt of the beam that can be compensated by mechanical rotation of the mixer block for about 0.6 degree. The phase error across the beam is less than 1/16 of the wavelength (Fig. 1b) thus being below the RMS accuracy of the telescope dish.

The results of aplanatic focusing are presented in Fig. 2(a) and Fig. 2(b). Strong diffraction effects are clearly seen within the main lobe along with essentially larger phase slope. The summary of criteria (1)-(3) presented in Table 1 shows faster degradation of the beam efficiency for the case of aplanatic focusing, but it remains higher than elliptical one. However, the aplanatic focus, unlike elliptical one, does not maintain the constant beam-width, so its correction (if any) cannot be a simple rotation. Some concerns are arising from the fact that intervening optics is necessary for the aplanatic lens-antenna. We do not analyze this problem here.

The aperture truncation analysis presented in Fig. 3 is using a few Gaussian beams of different half-power width (20, 30 and 60 degree) as they were launched by the feed located in the point of elliptical focus. It is obvious that much better Gaussisity (and beam efficiency) can be achieved, if the synthesis of a narrow-beam printed antenna is possible.

Fig. 4(a) and Fig. 4(b) demonstrate the difference between double-dipole and double-slot feed antennas. The far-field pattern of the double-dipole antenna, calculated inside the silicon lens in presence of misalignments, shows its better stability and potentially lower truncation level than for the double-slot antenna. This can be explained by the doubled number of elements of the array-antenna due to image provided by the back reflector.

IV. BALANCED QUASIOPTICAL MIXER

The layout of the new balanced quasioptical SIS mixer is presented in Fig. 5. The mixer employs two double-slot antennas, which are crossing each other in the areas of minimum *rf* current [9]. We have confirmed with CST MWS software that the beam quality (shape and efficiency) of the cross-slot antenna is generally the same as presented in Fig. 1. Each antenna receives one of two orthogonal polarizations, the LO and the signal. The signal beam is coupled from two vertical slots into twin-SIS mixers, Mixer 1 and Mixer 2, exciting them in anti-phase. The LO power is combined from two horizontal slots using a RF balun, then split in half and supplied to the mixers in-phase. This prevents coupling of LO power to the signal beam and vice versa. The LO balun is simulated providing phase shift of 180±14º across the band as presented in Fig. 6. Since the phase slope of the RF balun is small, the essential tilt of the LO beam can hardly be expected across the RF band. To combine signals from two mixers within 4-12 GHz IF bandwidth, the optimization of the half-wave balun is made. It is important to note here that the antenna beam pattern of the balanced quasioptical mixer will be formed via interference of two IF signals, since they preserve the RF phase information.

Assuming the dynamic resistance of SIS mixers Rd = 290 Ω the optimum balun characteristic impedance is found as 135 Ω, and its length is 4206 μm. The characteristics of the IF balun circuit are presented in Fig. 7 and Fig. 8. Resulting beam properties are shown in Fig. 9 as a set of far-field beam patterns and in Fig. 10 as a plot of integral efficiencies.

V. EXPERIMENTAL QUASIOPTICAL MIXER RESULT

Along with numerical studies on relatively complex quasioptical balanced SIS mixers, we designed a simpler double-slot antenna mixer [10], which is aiming to facilitate the general development of SIS structures including waveguide mixer for ALMA Band-10. Simulation predicted T_{RX} below 200 K (DSB) for such a mixer, if a good-quality Nb-AlO$_x$-Nb twin-junction is implemented into a NbTiN/SiO$_2$/Al microstrip. Since now we got samples with epitaxial NbN twin-SIS junction ($R_nA = 18$, $A = 0.5\ \mu m^2$) implemented into NbN/SiO$_2$/Al microstrip made in NiCT [11]. This type of SIS mixer is being studied for the first time. The mixer chip of size 2,45 mm x 2.45 mm x 0.3 mm made of MgO ($\varepsilon_{MgO} = 9.6$) was mounted with a 10-mm diameter silicon lens ($\varepsilon_{Si} = 11.7$), which does not have any anti-reflection coating, in the elliptical focusing position, $L_{ext} = 1.95$ mm. The IF chain was connected to the mixer block with a 15-cm coaxial cable followed by a 4-8 GHz isolator. The noise temperature of the IF chain was estimated with the mixer's shot noise being about 10-15 K within the 4-8 GHz IF band. The measured mixer gain was -15 dB including optical losses of about 3.5 dB and resistive loss in the SIS tuning circuit of 3 dB. Correcting for the optics loss, we got noise temperature referenced to the (cold) antenna of the mixer of about 400 K as shown in Fig. 11. Using Tucker's theory [12] we calculated the available gain of the mixer as -7 dB. This value is about 1.5 dB larger than our experimental estimate. This discrepancy can be explained with losses due to combined effect of long bonding wires (1.5-2 mm) and relatively long coaxial cable. The noise of the SIS mixer is estimated as 130 K that can be explained by presence of the multiple Andreev reflection [13]. The experiment has verified the effective magnetic field penetration depth of the tuning circuit NbN(200 nm)/SiO$_2$(250 nm)/Al(350 nm) being about 300 nm.

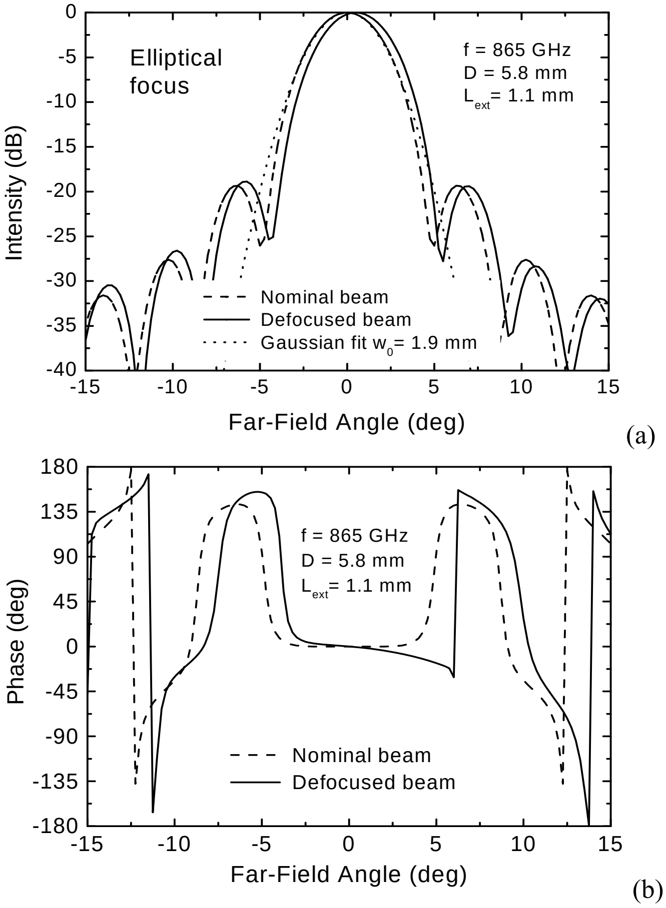

Fig. 1. E-plane beam patterns of double-slot lens-antenna (vibrator length, L = 100 μm, distance between two vibrators, W = 54 μm) calculated for elliptical focusing position (extension from center, $L_{ext} = 1100$ μm) for case of combination of misalignment factors listed in Table 1. (a) Effect of beam tilt. (b) Distortion of phase characteristic.

TABLE I.
MISALIGNMENT FACTORS AND THEIR EFFECT ON BEAM EFFICIENCY OF THE LENS-ANTENNA TWIN-SIS MIXERS.

	Elliptical focus		Aplanatic focus	
	Nominal position of feed	Mask offset 1 μm SIS area 20% Y-offset 10 μm Z-offset 20 μm ARC offset 10 μm	Nominal position of feed	Mask offset 1 μm SIS area 20% Y-offset 10 μm Z-offset 20 μm ARC offset 10 μm
Spillover efficiency (1)	80.2%	79.8%	85.8%	85.0%
Taper efficiency (2)	87.2%	86.6%	93.3%	92.5%
Aperture efficiency (3)	69.9%	69.1%	80.1%	78.7%

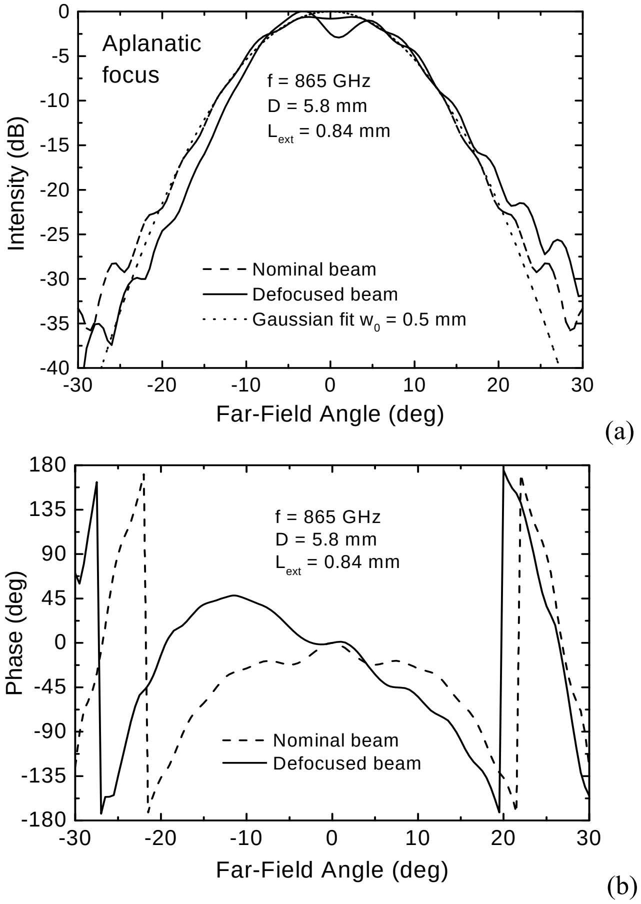

Fig. 2. E-plane beam patterns under the same conditions as Fig. 1, but the antenna is placed in aplanatic focusing position ($L_{ext} = 840$ μm): (a) effect of tilting and narrowing the beam; (b) distortion of phase characteristic.

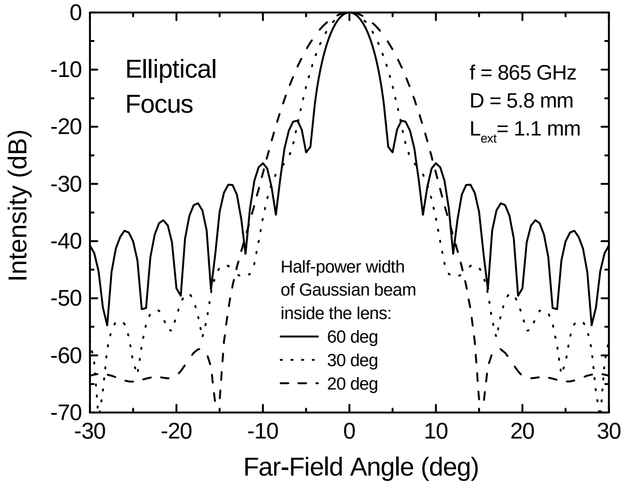

Fig. 3. Dependence of the lens-antenna beam on the beam-width of the feeding source. The gaussian beam launcher is combined with extended (L_{ext}=1100 µm) hemispherical immersion lens diameter 5.8 mm made of silicon. Note that the beam-width and sidelobe level are dependent on illumination angle of the lens.

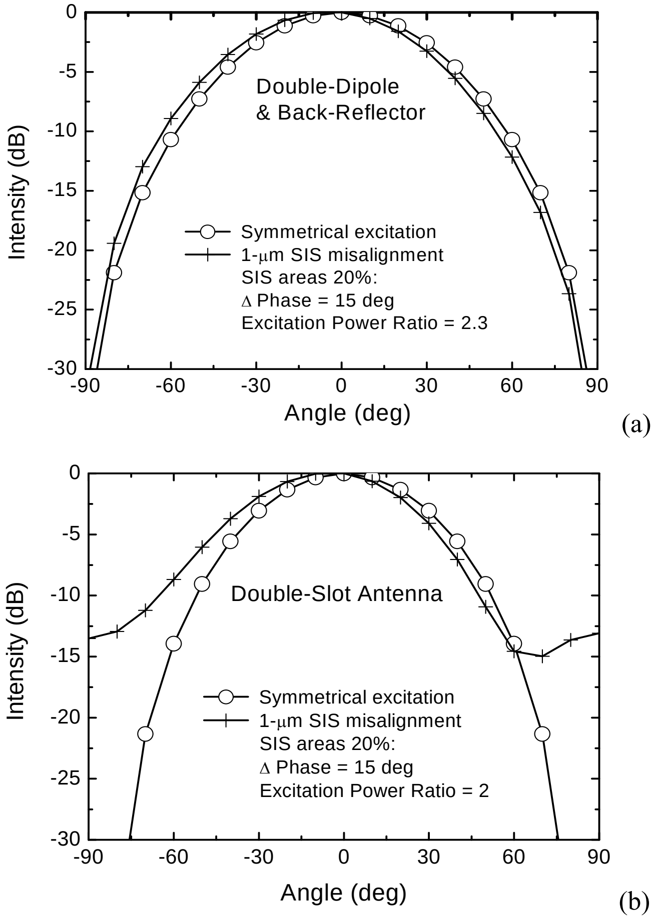

Fig. 4. Calculated illumination inside the silicon lens by (a) double-dipole antenna with back-reflector (L = 42 µm, W = 34 µm, distance to reflector 23 µm) and (b) double-slot antenna (L = 100 µm, W = 54 µm).

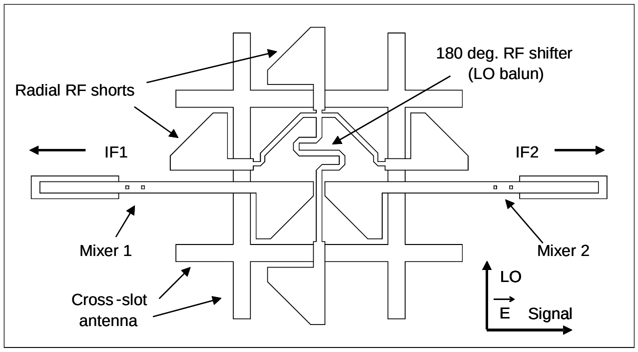

Fig. 5. Layout of the lens-antenna balanced SIS mixer. The output signals IF1 and IF2 are essentially anti-phased and must be combined at the output of an IF balun (not shown). The balun phase delay may change across IF band the 4-12 GHz IF band that may cause some tilt of the beam of the printed antenna array.

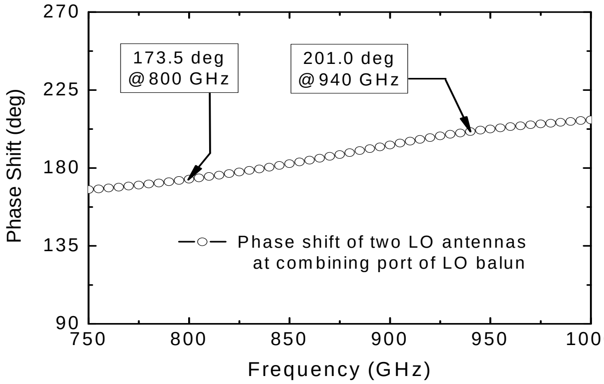

Fig. 6. Phase characteristic of 180-degree RF shifter (LO-balun) circuit of the quasioptical balanced mixer from Fig. 5.

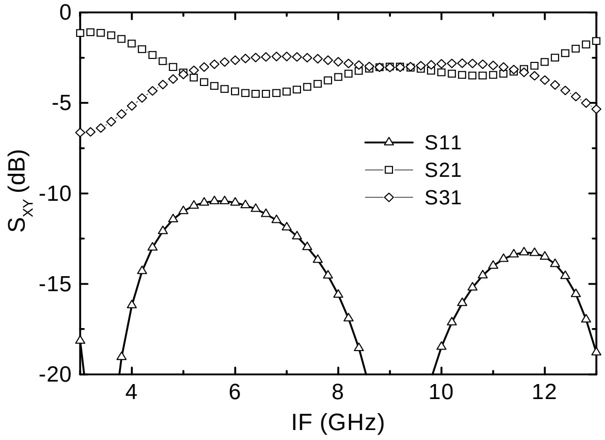

Fig. 7 Amplitude characteristics of an optimized 4-12 GHz IF balun (L = 4206 µm, Z_0 = 135 Ω) of the quasioptical balanced SIS mixer from Fig. 5: S_{11} stands for reflection at the combining point connected to IF amplifier Z_{in}= 50 Ω, S_{21} and S_{31} are transmission coefficients from IF ports of the two mixers.

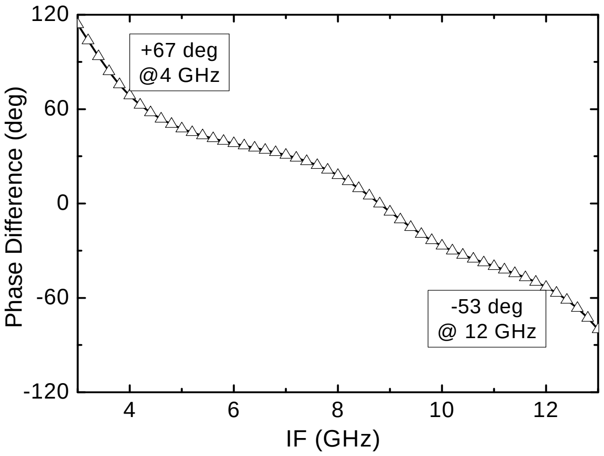

Fig. 8 Phase characteristics of an optimized 4-12 GHz IF balun of the quasioptical balanced SIS mixer from Fig. 5

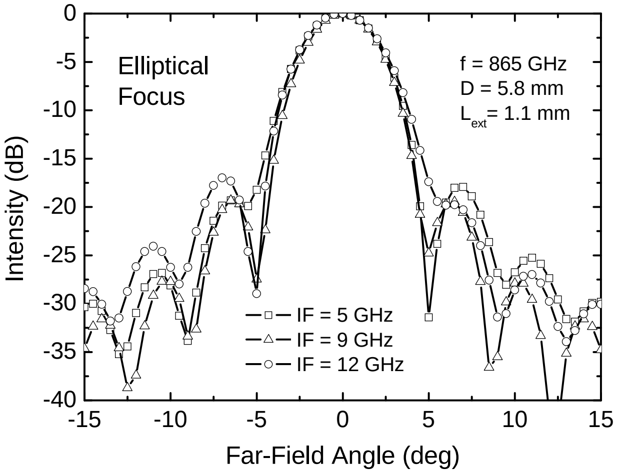

Fig. 9 Beam profiles calculated for a balanced quasioptical SIS mixer from Fig. 5 within IF-band 4-12 GHz.

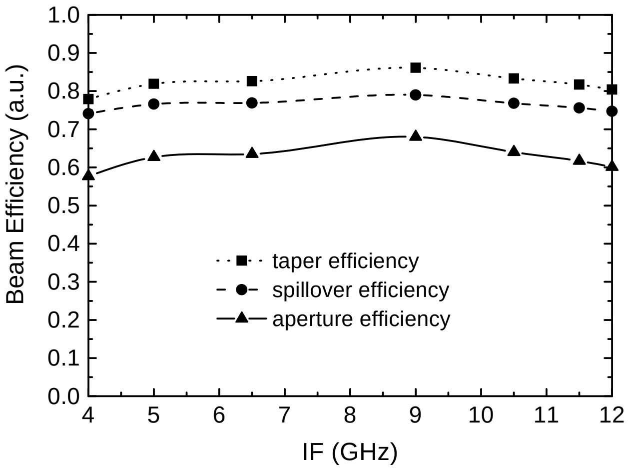

Fig. 10 Beam efficiency calculated for a balanced quasioptical mixer from Fig. 5 at 865 GHz. Note that the beam of the two-antenna array is defined for a balanced mixer by the interference of two signals at the output of the IF balun circuit.

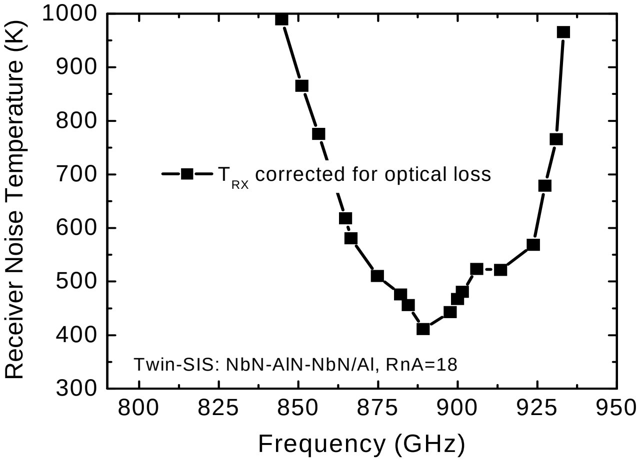

Fig. 11 Preliminary result on noise temperature (DSB) of quasioptical double-slot antenna receiver (L=100 μm, W=54 μm) in elliptical focusing position (D=10 mm, L_{ext}=1950 μm). The main goal of this test device is to attain parameters of a particular circuit with epitaxial NbN SIS junctions [11].

VI. CONCLUSIONS

The tolerance analysis has demonstrated that the behavior of a lens-antenna is dependent on the type of focusing (elliptical vs. aplanatic) and on the antenna-feed design (double-slot vs. double-dipole with back-reflector). Misalignment of the lens feed with respect to the optical axis brings the greatest beam distortion, and the effect of multiple misalignments can be characterized as the tilt of the beam with a few percent drop of the integral beam efficiency. It looks possible in most cases to correct the beam tilt by the mechanical rotation of the lens-antenna mount about its phase center. For doing this correction efficiently, no near-field intervening optics is desirable in front of the lens-antenna. In spite of the better integral efficiency of the aplanatic focusing, the combined effect of the misalignment and the intervening optics (accounting for its loss) can be a source of additional beam distortion that has to be studied in more details.

The numerical study of the new balanced quasioptical mixer demonstrates that reasonable stability of its beam over an IF band of 4-12 GHz can be achieved with a relatively simple balun circuit.

The noise temperature of 400 K (DSB, corrected for optical loss) is demonstrated at 890 GHz for a new double-slot antenna SIS mixer employing epitaxial NbN twin-SIS junction and Al-wiring. This result is verified with Tucker's theory being limited by the quality of the IV-curve and by loss in the NbN/SiO_2/Al tuning circuit. To understand the relatively high noise of the NbN SIS mixer, the effect of multiple charge transfer (Andreev reflection) has to be taken into account.

We hope that present research can help in separating the problems of effective utilization of lens-antennas into two groups: i) beam distortions caused by the design of a lens-antenna itself and ii) distortions arising from properties of the extended optical path including effects of truncating apertures, ghost reflections, etc.

ACKNOWLEDGMENT

Authors thank M. Ishiguro, T. Hasegawa, J. Inatani, T. de Graauw, H. Matsuo, M. Candotti, S. E. Bankov and J. Zmuidzinas for encouragement and many fruitful discussions.

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