A Broad Bandwidth Suspended Membrane Waveguide to Thinfilm Microstrip Transition

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Abstract

Excellent progress in the development of Submillimeter-wave SIS and HEB mixers has been demonstrated in recent years. At frequencies below 800 GHz these mixers are typically implemented using waveguide techniques, while above 800 GHz quasi-optical (open structure) methods are often used. In many instances though, the use of waveguide components offers certain advantages. For example, broadband corrugated feed-horns with well defined on axis Gaussian beam patterns.

Over the years a number of waveguide to microstrip transitions have been proposed. Most of which are implemented in reduced height waveguide with RF bandwidth less than 35%. Unfortunately reducing the height makes machining of mixer components at terahertz frequencies rather difficult. It also increases RF loss as the current density in the waveguide goes up, and surface finish is degraded.

An additional disadvantage of existing high frequency waveguide mixers is the way the active device (SIS, HEB, Schottky diode) is mounted in the waveguide. Traditionally the junction, and its supporting substrate, is mounted in a narrow channel across the guide. This structure forms a partially filled dielectric waveguide, whose dimensions must kept small to prevent energy from leaking out the channel. At frequencies approaching or exceeding a terahertz this mounting scheme becomes impractical. Because of these issues, quasi-optical mixers are typically used at these small wavelength.

In this paper, we propose the use of suspended silicon (Si) and silicon nitride (Si_3N_4) membranes with silicon micro-machined backshort and feedhorn blocks. Deposited on the membrane is a "single sided" thinfilm radial probe which extrudes partly into the waveguide. To simplify eventual assembly, the membrane based radial probe is oriented orthogonal to the E-field in the guide. The proposed waveguide to microstrip transition is a variation on the rectangular probe design that finds a wide range of use at the lower microwave and millimeter wave frequencies.

Extensive 3D electromagnetic field simulations are reported in this paper. It is found that the a thinfilm radial probe on top of a suspended membrane is able to couple with 85% efficiency to an entire TE10 mode dominated waveguide bandwidth. This includes a 0.5 dB loss in the 0.035 λ_o "air" space above and directly below the suspended membrane. The input impedance of the probe is seen to be insensitive to airgap variation beneath or above the membrane. When combined with micromachining techniques, the discussed transition enables technology transfer to large RF bandwidth spectroscopic imaging arrays at terahertz frequencies.

Keywords

Suspended membrane, waveguide to thinfilm microstrip transition, radial probe, micromachining, hot electron bolometer (HEB), superconducting-insulating-superconducting (SIS) tunnel junction, array receivers.

I. Introduction

The majority of SIS mixers (and most of the non-quasi optical HEB mixers) to date employ planar circuit probes that extend all the way across the waveguide [1]-[3]. An important reason for the popularity of this kind of probe is the convenience with which the active device can be biased, and the IF signal extracted. Unfortunately this kind of "double-sided" probe exhibits a poor instantaneous RF bandwidth when constructed in a full-height waveguide ($\leq 15\%$). When the waveguide height is reduced by half, the probe bandwidth improves dramatically to a maximum of $\approx 33\%$ [2]. However, reducing the height can result in significant fabrication problems (cost) and increased RF loss, especially at frequencies near or above a teraherz.

An alternative approach to the "double-sided" probe is one that does not extend all the way across the waveguide. For this kind of probe, referred to from now on as a "one-sided" probe, the modal impedances add in series. The real part of the input impedance only comes from the single propagating mode and is relatively frequency independent. These probes are typically implemented in full-height waveguide which minimizes conduction loss and eases fabrication complexity at terahertz frequencies. Though a rectangular version of the "one-sided" probe is used quite extensively by microwave engineers [4][5] and was introduced to the astrophysical community by Kerr *et al.* [6] in 1990, it is seen to be fundamentally different from the proposed radial shaped probe. Experimentally we have found a constant radius probe implemented in the described thin-film configuration to give vastly superior performance over the more traditional approach.

Regardless though of what method is used for coupling to the waveguide, the issue remains of how to physically mount the junction. To circumvent the difficulty of hand-mounting tiny substrates (on which the active devices are deposited) we decided to explore a membrane morphology[3][7]. As it turns out, this technology is easily extended to array applications at both submillimeter and terahertz frequencies.

Hot electron bolometers (HEB's) are the mixing element of choice in the teraherz regime and have, by virtue of their simplicity, a very large fractional RF bandwidth. To find a suitable match, we have investigated a variety of fixed tuned and frequency scalable full-height waveguide transitions. We find that a constant radius "single-sided" probe with a 90° fan angle is able to couple very efficiently to a full-height waveguide over nearly a 50% fractional bandwidth[8][9]. Because HEB's come in two styles, diffusion cooled[10] and phonon cooled [11][12], it is natural to look into what kind of membrane is most suited for the device of choice.

Phonon and diffusion cooled HEB mixers function by different mechanisms based on the way thermal energy of the hot electrons is removed. In the case of the phonon cooled HEB's, the electron-phonon coupling is the main cooling mechanism. Thus a fast phonon escape time is required, and the superconducting films (NbN) are typically made very thin (3-5nm). To facilitate the cooling of these devices we have opted for the use of a 7 μm thick silicon substrate. As far as the diffusion cooled HEB's are concerned, their main cooling mechanism is thru the contact electrodes (Au). The diffusion cooled HEB could also use a silicon membrane, but in theory performs just as well on a 1 μm thick silicon nitride (Si_3N_4) membrane. We find that both membrane styles give similar RF performance, though the

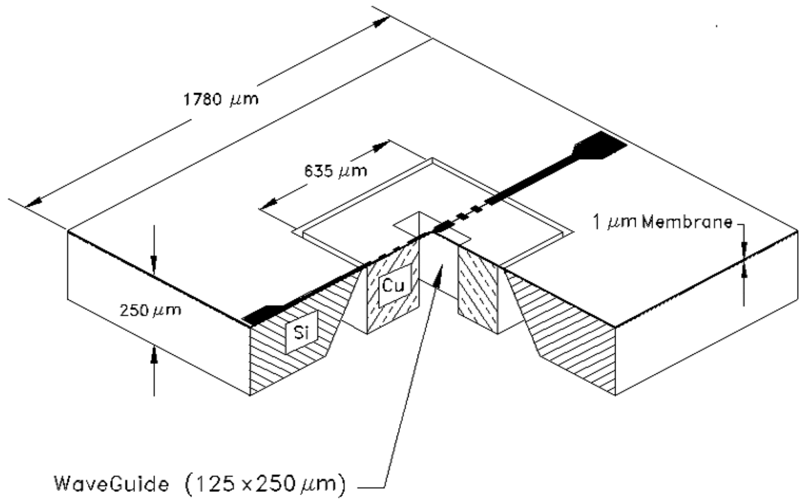

Fig. 1. Isometric view of the original (850 GHz) contacting 1 μm thick silicon nitride membrane. Deposited on top of the membrane is a “double-sided” probe which has a instantaneous RF bandwidth of $\approx$ 4-5%. Input impedance is 40-j20 Ω, and the waveguide is full height.

1 μm silicon nitride membrane is likely to be the easier one to scale to THz frequencies. It should be noted that GaAs is a viable alternative to the use of silicon as a membrane[7].

II. Suspended Membrane Morphology

In Fig. 1 we show an isometric view of a 1μm thick silicon nitride (Si_3N_4) membrane on top of it's silicon support structure. An across the guide "two-sided" probe[1][3] is connected to a niobium based SIS junction. This particular device had been in use at the Caltech Submillimeter Observatory (CSO) in 1997-1998, until it was upgraded to an all NbTiN based quasioptical SIS mixer [13]. Recent computer simulations[14] suggest this structure has a 4-5% instantaneous bandwidth, which in fact has been confirmed by measurement on the actual device. In this particular design we had the membrane physically touch the base pedestal (Fig. 1). In practice this proved very difficult as the membrane tended to break upon contact with the pedestal. To make matters worse, simulations show that the performance of the membrane probe is critically dependent on the airgap directly beneath it. Being aware of these shortcomings, and having powerful electromagnetic field simulators to our disposal[14][15], we endeavored upon a new design.

We require the silicon nitride membrane to be suspended by 12 μm on both top and bottom. Based on experience, suspending the membrane significantly increases reliability and eases assembly. In practice it means that the backshort and horn blocks will be separated by 25 μm. Though the “air” gap is quite large ($\approx \lambda_o/15$), it does guarantee the design can be scaled to terahertz frequencies. Unfortunately, the open space can cause higher order (evanescent) modes to be excited, possibly degrading the overall mixer performance. The solution is to use “photonic crystals junctions” as described in a recent paper by Hesler [16] *et al* (Fig. 2). Essentially these cells act as quarter wave RF choke structures, and scatter/block the RF fields. Simulations show that they are only needed in the horn (top) block. Placing them underneath the membrane does not appear beneficial. Since we plan to laser micro-

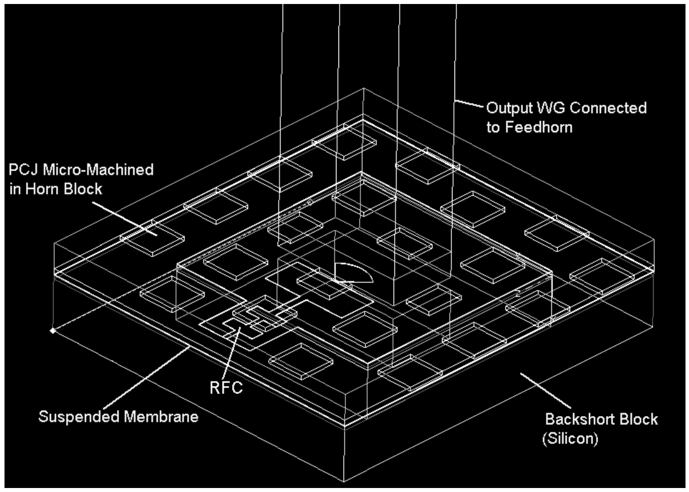

Fig. 2. Layout of the silicon micro-machined backshort and horn block. The membrane is suspended by 12 μm. Photonic crystals in the horn (top) block are used to scatter fields leaking into the airgap between the blocks. The first RF choke section is positioned on top of the suspended membrane, while the remaining two sections are directly on silicon. IF and bias lines run over the RF choke to the edge of the substrate. Simulated fixed tuned RF bandwidth is 50%, radial probe impedance locus of $\approx 50\ \Omega$.

machine [17] the backshort and horn block out of silicon, adding photonic crystals is trivial. The physical dimensions of the cells (f_o = 900 GHz) are: 76 x 76 x 8 μm. As discussed, we have opted for the use of a "one-sided" thinfilm radial probe to microstrip transition, as simulations[9] have shown the potential for huge fractional bandwidth ($\approx$ 50%).

III. Assembly Diagram of the Focal Plane Array

The eventual goal of the suspended membrane design is to integrate it into a large focal plane array assembly. In Fig 3 we show such an array, composed of a silicon backshort, membrane and feedhorn block. Backshort pedestals are formed by patterning and than anisotropic wet etching a silicon waver along it's (111) crystal plane (54.7° from the 100 plane). Using laser micro-machining techniques we then etch the rectangular backshort to the correct depth.

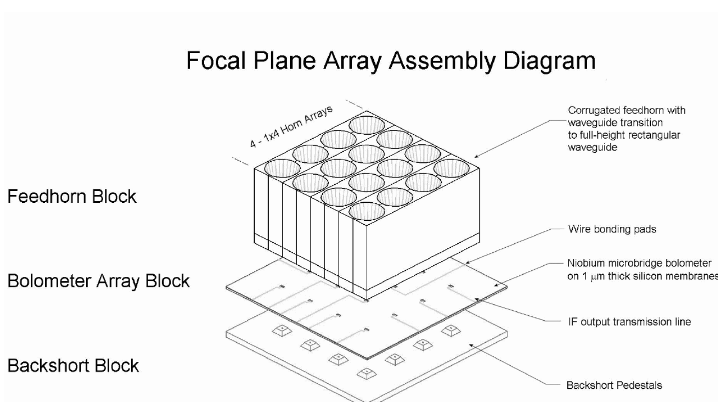

Fig. 3. Assembly diagram of the focal plane array.

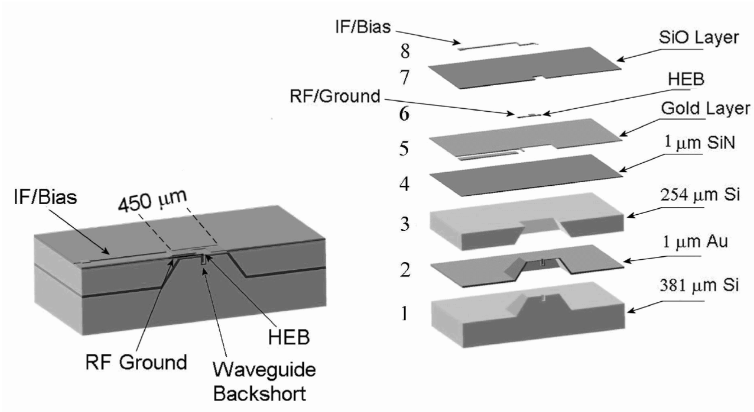

Fig. 4. Cross section of membrane block.

The membrane (bolometer array) block is then stacked on top of the backshort block, leaving a gap between it and the membrane. IF and bias lines are taken to wire bonding pads located along the edge. The horn block consists of an array of micro-machined corrugated feedhorns with circular to rectangular full height waveguide transitions. The whole structure will be cooled to the operating temperature of HEB's (4.3 - 1.5 K). We do not anticipate thermal problems cryo-cooling the array, partly because the array is very homogeneous (no metal parts), but also because silicon has a very low thermal coefficient of expansion. In Fig 4 we show a detailed cross section of the waveguide backshort and membrane block. We start with a 381 μm silicon (100) wafer. Once the backshort is machined, it is covered with a 1 μm Au layer. Next we take a 254 μm silicon (100) waver, and grow a silicon nitride (Si_3N_4) membrane on top of it to a thickness of 1 μm. This is done by means of low-pressure chemical vapor deposition (LPCVD). In the next few steps we deposit the HEB microbridge, the contacts leads, and the Au wiring. Finally, we lithographically mask off the bottom of the bolometer array block and wet etch all the way thru along the (111) crystal plane using the Si_3N_4 layer on the other side as an etch stop. The IF and bias lines will be taken out over the RF choke to the side of the membrane.

IV. Simulation results on a 1 μm Silicon Nitride (Si_3N_4) Membrane

The use of suspended membranes with either phonon or diffusion cooled hot electron bolometers (HEB's) lends itself well to spectroscopic imaging array applications at both the upper submillimeter and terahertz frequencies. The full-height waveguide to thinfilm microstrip probe transition under discussion is centered at 900 GHz and constructed on a 1 μm silicon nitride membrane. A close up view of the proposed configuration is shown in Fig 5. In the rendered view we have omitted the 1 μm Si_3N_4 membrane layer for clarity. A six section RF choke connects to the metalization layer (ground) around the perimeter of the membrane. The purpose of the choke is to establish a ground potential (short circuit) at the waveguide wall. Though this structure is bandwidth limiting, it does not appear to impact in band performance of the thinfilm radial probe transition significantly. There is a 450 x 450 x 12 μm air pocket directly underneath the radial probe and first two sections of the RF choke.

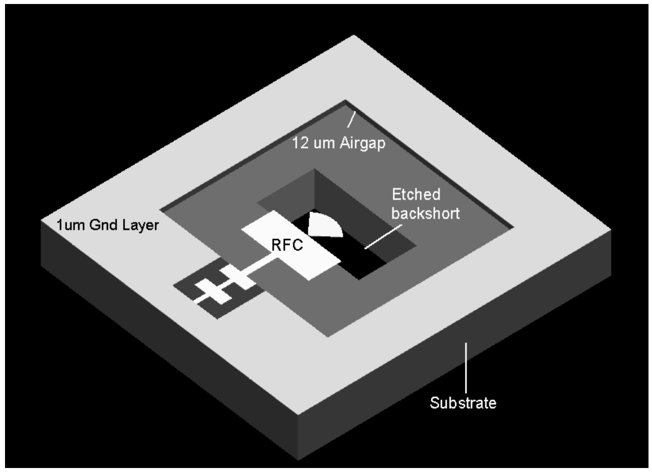

Fig. 5. Rendering of probe on silicon membrane. In the rendering we have omitted the membrane for clarity. The waveguide is full-height (272 x 136 μm), and the probe radius 62 μm.

Note that the first two quarter wave sections are on top of a suspended membrane (Keff$_{low}$=1.09, and Keff$_{high}$=1.20). The dimension of the first low (11 Ω) impedance section is 180 x77 μm. It's width is set to be half a wavelength at 1150 GHz. The high impedance suspended RF choke section is 68 Ω (15 x 74 μm in size). The remaining four choke sections are on silicon, and their dimensions are 70 x 26 μm and 10 x 31 μm respectively. Optimal backshort distance as referred to the bottom of the membrane is 86 μm.

The IF (not shown) is taken out of the side of the probe and routed via a RF choke and CPW transmission line to the edge of the membrane. Taking the IF out this way has the

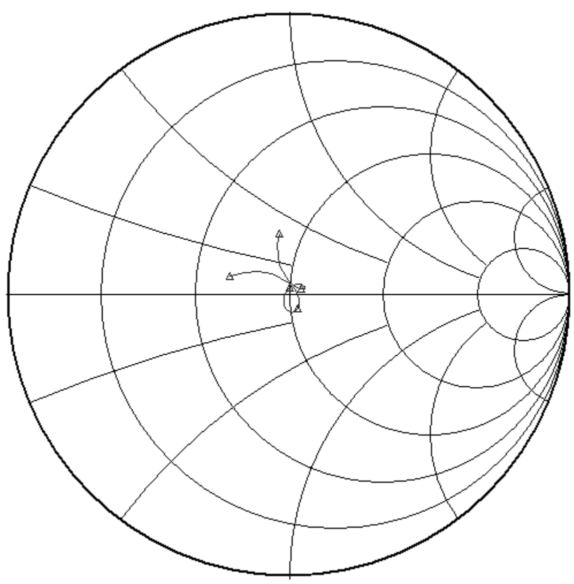

Fig. 6. Impedance of a thinfilm radial probe on a suspended 1 μm Si_3N_4 membrane. Th RF bandwidth is somewhat limited by the RF ground. Smith chart is normalized to 50+j14 Ω.

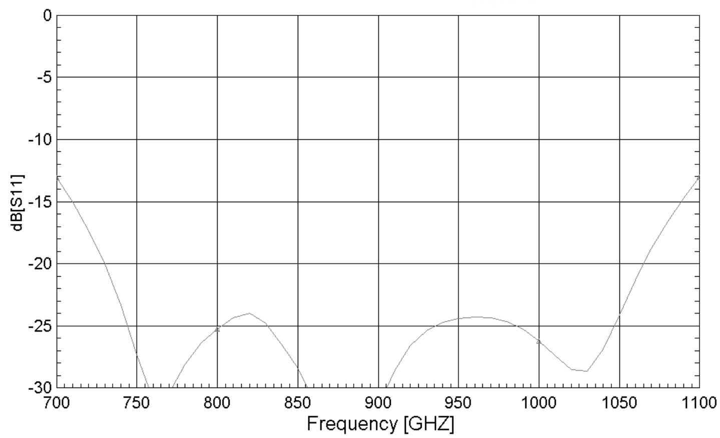

Fig. 7. Input return loss of a 1 μm thick silicon nitride membrane. The membrane is suspended symmetrically with 12 μm space on both top and bottom. Total backshort and horn block separation is 25 μm. Probe radius 62 μm.

advantage that the metalization is planar and no complicated processing is required.

The probe impedance and return loss are shown in Figs. 6 and 7. The probe is slightly inductive, $50 + j14\ \Omega$. Note that the the design is centered on the 350 μm atmospheric window, which extends from 780-1060 GHz. Measured at a return loss of -20 dB (VSWR=1.2), the probe's instantaneous bandwidth is essentially a full waveguide bandwidth. This is a good match to both the large intrinsic bandwidth of hot electron bolometers (HEB's), and the ground based atmospheric transmission window of a high and dry site such as the Southpole.

V. Sensitivity to height misallignment

In practice it is extremely difficult, if not impossible, to align the membrane to better than a few micrometers in the height dimension. Fortunately this is not necessary as we show in Fig 8. Here we simulate the effect of raising (or lowering) the membrane by 6 μm. The net effect is negligible, largely because the change in suspension height has a minimal

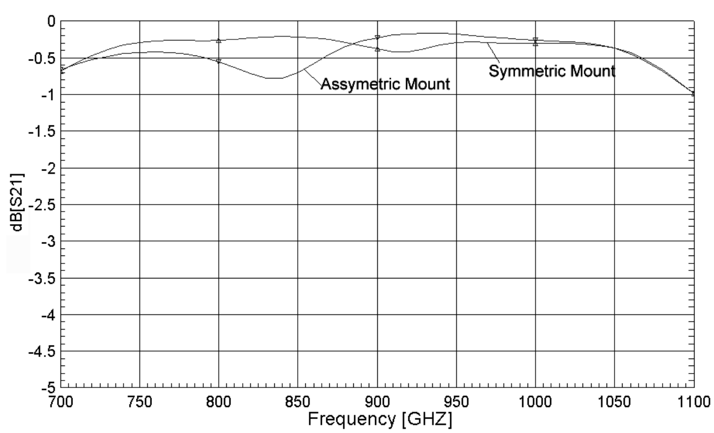

Fig. 8. Effect of height misalignment (6 μm) of the silicon nitride membrane under discussion.

effect on the membrane's effective dielectric constant. Note that even in the case of perfect symmetry, power coupled to the horn block is no more than -0.5 dB. Since we have used perfect conducting metals in our computer simulations, it must mean that approximately 10% of the incident power leaks out into the 25 μm space between the backshort and horn block. It is evident that the photonic crystals (Fig. 2) are able to prevent excitation of higher order modes even though the space between the blocks is too large to prevent loss of power. Increasing the block separation makes, as one would expect, matters exponentially worse. Based on extensive computer simulations, a space $\leq \lambda_o/15$ is deemed acceptable.

VI. Simulation results with a 7 μm silicon membrane

For phonon cooled HEB's[11], the main cooling mechanism of the hot electrons are phonons escaping into the substrate. As such, very thin Si_3N_4 membranes are probably not suitable substrates for these devices. As an alternative we propose the use of a 7 μm thick silicon membrane[18]. Note that the results are equally applicable to thin GaAs substrates, as the respective dielectric constants are nearly the same (ϵ_r Si = 11.7 and ϵ_r GaAs = 12.9). In Fig. 9 we show a 3D rendering of the silicon membrane and backshort block stacked together. The silicon membrane design is similar to the silicon nitride (Section IV) membrane, in that they are both suspended. However, simulations indicate that from a RF coupling efficiency viewpoint, it is better to keep the total separation between horn and backshort block $\leq \lambda_o/15$ (25 μm at 900 GHz). In case of the 7 μm thick silicon membrane, it is therefore advisable to decrease the space underneath the membrane to 6 μm, as opposed to 12 μm for the 1 μm thick Si_3N_4 membrane. Note that the space above the membrane remains 12 μm. This space is needed for photonic crystals[16] which scatter, and interfere with, high order modes that can be excited in the space between the horn block and membrane.

Unlike the silicon nitride membrane, we cannot simply use a solid silicon membrane. Not only has the thickness increased from 1 μm to 7 μm, the material dielectric constant has also increased ($\epsilon_r = 7 \rightarrow \epsilon_r = 11.7$). Net effect being that a significant amount of energy

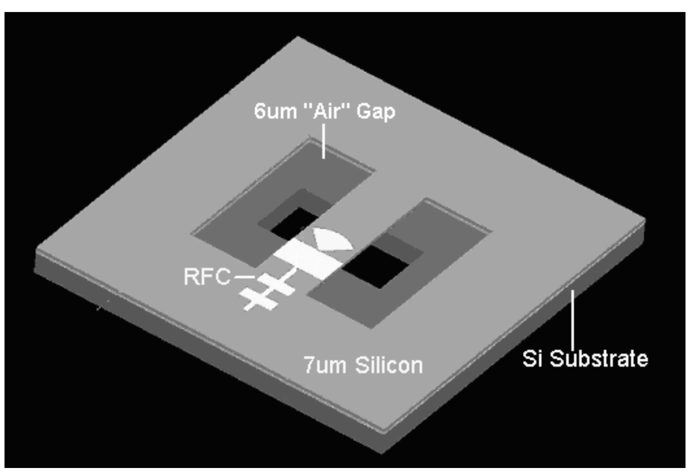

Fig. 9. Cutout of a 7 μm silicon membrane radial probe. The channel width is 110 μm, waveguide dimensions are 272 x 136 μm, backshort distance from the bottom of the membrane 43 μm, and the optimal probe radius 62 μm.

is able to propagate inside the much thicker silicon membrane. The answer is to etch away enough substrate so as to leave only a thin, below cutoff, silicon channel [7].
That is to say,

$$a < \frac{c}{2 f_{max} k_{eff}} \quad (1)$$

where a is the width of the dielectric loaded channel, f_{max} the maximum operating frequency of interest, and k_{eff} the effective dielectric constant of the suspended substrate (1.09 for 7 μm thick silicon suspended by 6 μm of air).

To get a feel for the RF attenuation due to substrate loss, we ran several simulations in which we changed the resistivity of the silicon membrane from 100 to 5000 Ω-cm. We found the attenuation to be insignificant for $\rho > 100$ Ω-cm. It should be noted that the resistivity of silicon increases upon cryo-cooling as most of the carriers freeze out.

Referring to Fig. 9, the six section RF choke connects to the metalization layer (ground) around the perimeter of the membrane (see also Fig. 12). As was seen, the purpose of the choke is to establish a ground potential (short circuit) at the waveguide wall. There is a 400 x 376 x 6 μm air pocket directly underneath the radial probe and first two sections of the RF choke. Note that the first two quarter wave sections of the choke are on top of a 6 μm suspended membrane (k_{eff} low=3.0, and k_{eff} high=1.8). The dimension of the first low (17 Ω) impedance section is 110 x 63 μm. The channel width is 110 μm and is set to have a TE_{10} mode cutoff for frequencies below ≈ 1150 GHz (1). Referring to Fig. 9, the etched window dimensions (w x h) are 145 x 364 μm. The high impedance suspended RF choke section is 63 Ω (10 x 51 μm in size). The remaining four choke sections are on silicon, their dimensions are 70 x 25 μm and 10 x 28 μm respectively. Optimal backshort distance referred to the bottom of the membrane, given a 6μm airgap underneath the substrate, is 43 μm.

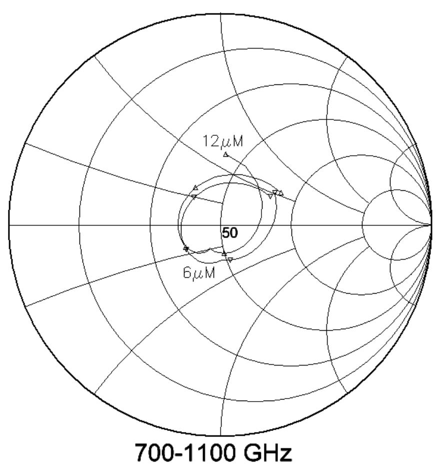

Fig. 10. Input impedance, and sensitivity to height misallignment (6 μm → 12 μm) of the proposed 7 μm thick silicon membrane. Though not apparent from the Smith chart, RF loss in the space between the backshort and membrane increases significantly for an “air” gap > 6 μm. Smith chart is normalized to 50 Ω

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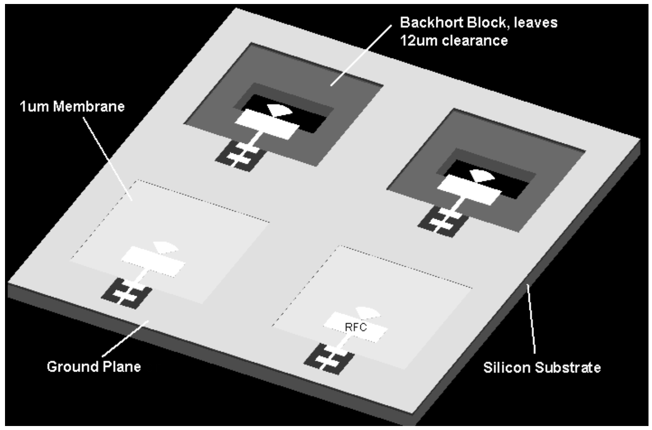

Fig. 11. Rendering of a 2 x 2 pixel 1 μm thick silicon nitride membrane array. The Si_3N_4 membrane is grown on top of a 254 μm thick silicon waver. The backshort block (dark-grey) comes to within 12 μm of the membrane (see also Fig. 4). For clarity we have omitted the membranes in the top two pixels.

In Fig. 10 we show the probe impedance from 700-1100 GHz. It's locus happens to be nicely centered at 50 Ω. As we have seen with the silicon nitride membrane, sensitivity to height is minimal. However, unlike the situation with the Si_3N_4 membrane, raising the "air" space from 6 μm $\rightarrow$ 12 μm adversely effects the power coupling efficiency to the horn block. A upper limit for the "air" gap is about $\lambda_o/15$ at the center of the band. Note that the the design is centered on the 350 μm atmospheric window, which extends from 780-1060 GHz.

VII. Simulations on 2 x 2 element membrane arrays

The primary interest of this work is the development of large scale HEB based spectroscopic imaging arrays. Now that the individual membrane and waveguide transitions are understood, it is of interest to measure cross-guide coupling in an array geometry. This is especially relevant as there is power ($\approx 10\%$) in the 25 μm space between horn and backshort block. In order to investigate this potential problem, we have run 3D computer[14] simula-

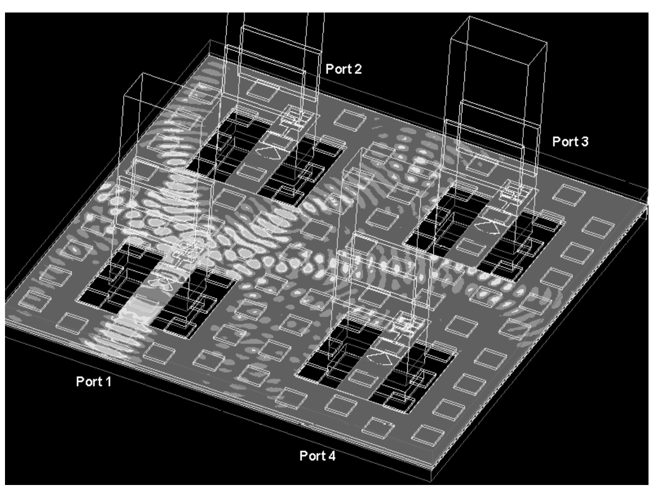

Fig. 12. E-field distribution on the surface of 2 x 2 silicon membrane array.

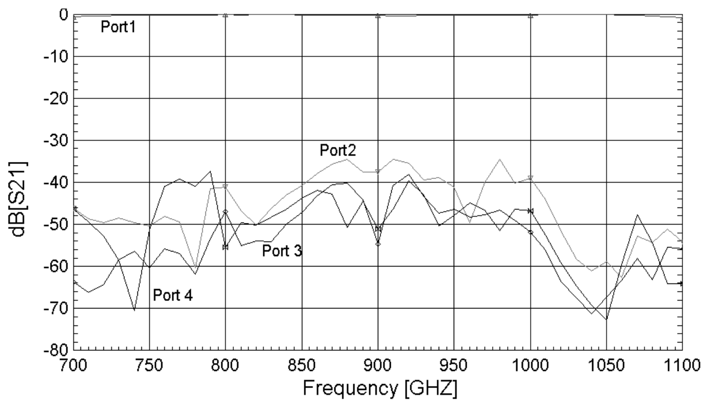

Fig. 13. Cross talk between the pixels (similar for both arrays).

tions on 2 x 2 element Si_3N_4 and silicon membrane arrays (Figs. 11 & 12). On top of the membrane are RF chokes that connect to the ground plane all around the perimeter. These provide short circuit references at the waveguide wall. The IF and bias lines run out over the choke structure to the edge of the membrane structure. In Fig. 12 we show the electric field distribution on the surface of a 2 x 2 silicon array. The interest is in understanding cross guide coupling, RF power loss, and the effect of the photonic crystals.

In Fig. 13 we show the crosstalk between the individual pixels. Though small, it is evident that there is indeed some power being coupled between the elements. The ≈ -40dB crosstalk level can be improved upon by reducing the space between the backshort and horn blocks.

Finally, we show the input return loss of the two types of membrane based thinfilm radial probe transitions. For an HEB device with RF input impedance of 50 Ω, the coupling efficiency appears better than 95% (-13 dB) over most of the frequency band. Given that the leakage of energy in the space between the backshort and horn blocks is on the order of 0.5 dB, we estimate the combined probe/membrane coupling efficiency to be ≈ 85%. Note that this loss does not include conduction loss in the probe, waveguide and feedhorn.

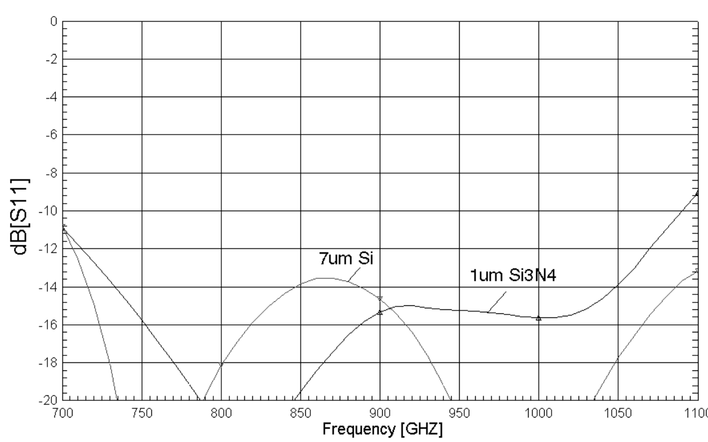

Fig. 14. Input return loss of pixels on both membrane types.

VIII. Conclusion

We have presented a systematic design study of a suspended membrane based radial probe waveguide to thinfilm microstrip transition. The design uses a full-height waveguide and is scalable to terahertz frequencies. The instantaneous (fixed tuned) bandwidth of the probe is on the order of 45%, and as such is ideally suited for use with large HEB based spectroscopic imaging arrays.

To facilitate both "phonon cooled" and "diffusion cooled" hot electron bolometers, we have implemented the design for 7 μm thick silicon and 1 μm thick Si_3N_4 membranes. The probe impedance is seen to be 50 Ω, which provides a good match to existing HEB mixer designs. Computer simulations indicate that the gap between the backshort and horn blocks should be kept to less than $\lambda_o/15$, or about 25 μm in the 700-1100 GHz frequency band. Even so, roughly 10% power is lost in the space between the blocks. For this reason we decided to use photonic crystal junctions to scatter, and otherwise minimize degrading effects, of higher order modes. Finally, it is seen that the cross coupling between pixels in an imaging array of membrane mounted HEB's is less than $\approx$ -40 dB. The exact details of the IF/Bias network are still under investigation.

IX. Acknowledgments

We wish to thank Goutam Chattopadhyay at Caltech for advice on the HFSS computer simulations, and professor Sigfrid Yngvesson at the University of Massachusetts and Dan Prober at Yale University for very helpful discussions on the subject of HEB mixers. This work was partially funded through NSF grant 9800260, NASA grant NAG5-9100, and Army Research Office grant DAAD19-01-1-0451 to the University of Arizona.

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