

RF current distribution in HEB and a 2-dimensional device model

P. Khosropanah^{*}, A. Adam[§], H. Merkel^{*}, S. Cherednichenko^{*},

S. Yngvesson[#], E. Kollberg^{*}

^{*}Chalmers University of Technology, Department of Microelectronics, Microwave electronics Laboratory, 412 96 Gothenburg, Sweden

[#]University of Massachusetts, Department of Electrical and Computer Engineering, Amherst, MA 01003

[§]Laboratoire de Génie Électrique de Paris, Groupe SFMD, 91192 Gif sur Yvette, France

Abstract

The RF current distribution in the bolometer bridge is investigated by solving the Maxwell's field equations analytically and by using commercial packages *QuickWave-3D*[®] (Finite-Difference Time-Domain, FDTD Method) and *Sonnet*[®] (Method of Moments). The outcomes of analytical calculations and *QuickWave-3D*[®] indicate non-uniform RF current distribution where *Sonnet*[®] results show completely uniform current at 2 THz. This controversial result is subject to discussion. By accepting the non-uniform scenario one can explain the dependence of the conversion loss on LO frequency. A 2-dimensional device model is presented which is based on non-uniform LO power absorption.

I. Introduction

In earlier one-dimensional models [1] RF heating is assumed to be uniform all over the bolometer bridge. The predicted conversion loss by such a model was far too high compared to measured data. Therefore a tuning factor was needed to fit the predicted conversion loss, receiver noise and output noise to the measured data. Recent work by Semenov *et al.* [2] has suggested a non-uniform heating across the bolometer bridge due to RF skin effect.

Since this effect is supposed to have a large impact on the bolometer performance the RF current distribution in the bolometer bridge is investigated in more detail.

In section II the RF current distribution in an infinite long NbN strip is calculated analytically. Section III presents the simulation results of various structures done by a FDTD package (*QuickWave-3D*[®] [3]). In section IV the effect of non-uniform RF current distribution on bolometer performance is discussed. Section V presents the outcome of a moment method approach (*Sonnet*[®] [4]). Finally the discussion and conclusion come in section VI.

II. RF current distribution in an infinite long resistive strip

In this section we derive an analytical expression for current distribution in an infinite long conductor strip. Figure 1 shows a schematic top view of a long strip.

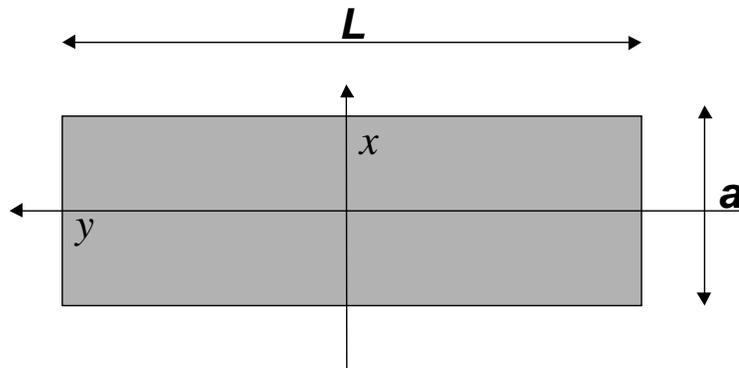


Figure 1. Top view of a long strip with length L and width a where $L \gg a$

Here it is assumed that the strip is resistive and electrically very thin. This is the case in NbN bolometer bridge which is 5 nm thick with conductivity about $3.5 \times 10^{-6} \Omega\text{m}$

The wave equation in a medium with finite conductivity is:

$$-\nabla^2 \underline{E} = -j\omega\mu(\sigma + j\omega\varepsilon)\underline{E}.$$

In our case $\sigma \gg \varepsilon\omega$. For NbN σ is about 3×10^5 S/m where $\varepsilon\omega$ is about 100 S/m at 2 THz. So the second term on the right hand side of the above equation is negligible and the equation is reduced to:

$$\nabla^2 \underline{E} = j\omega\mu\sigma \underline{E} \Rightarrow \nabla^2 \underline{E} = k^2 \underline{E}$$

where: $k^2 = j\omega\mu\sigma$.

The electric field in the strip can be written as: $\underline{E} = E_x(x)\underline{x} + E_y(x)\underline{y}$. Since we assume that the strip is infinitely long, the field does not depend on y along the strip. Under this assumption we get:

$$\nabla^2 \underline{E} = \frac{\partial^2 E_x}{\partial x^2} \underline{x} + \frac{\partial^2 E_y}{\partial x^2} \underline{y} = k^2 E_x \underline{x} + k^2 E_y \underline{y}$$

which implies:

$$\frac{\partial^2 E_x}{\partial x^2} = k^2 E_x \quad \text{and} \quad \frac{\partial^2 E_y}{\partial x^2} = k^2 E_y.$$

Assuming that the potential is constant across the strip, requires $E_x = 0$. So one is left with:

$$\frac{\partial^2 E_y}{\partial x^2} = k^2 E_y.$$

Solving for E_y gives: $E_y(x) = C_1 e^{kx} + C_2 e^{-kx}$.

Because of the symmetry we have: $E_y(-x) = E_y(+x)$, so $E_y(x) = C(e^{kx} + e^{-kx})$.

If I_0 is the total current and t is the thickness of the strip:

$$I_0 = t \int_{-a/2}^{a/2} j(x) dx = t \int_{-a/2}^{a/2} \sigma E_y(x) dx = t \sigma \int_{-a/2}^{a/2} E_y(x) dx = t \sigma \int_{-a/2}^{a/2} C(e^{kx} + e^{-kx}) dx =$$

$$t \sigma \frac{C}{k} [e^{kx} - e^{-kx}]_{-a/2}^{a/2} = t \sigma \frac{2C}{k} \left(e^{\frac{ka}{2}} - e^{-\frac{ka}{2}} \right) \Rightarrow C = \frac{kI_0}{2t\sigma \left(e^{\frac{ka}{2}} - e^{-\frac{ka}{2}} \right)}$$

And the final result becomes:

$$j(x) = \frac{kI_0}{2t\sigma} \frac{(e^{kx} + e^{-kx})}{\left(e^{\frac{ka}{2}} - e^{-\frac{ka}{2}} \right)}$$

Figure 2 shows the normalized amplitude of $j(x)$ inside the NbN strip at 0.6, 1.6 and 2 THz for 2 micron wide strip.

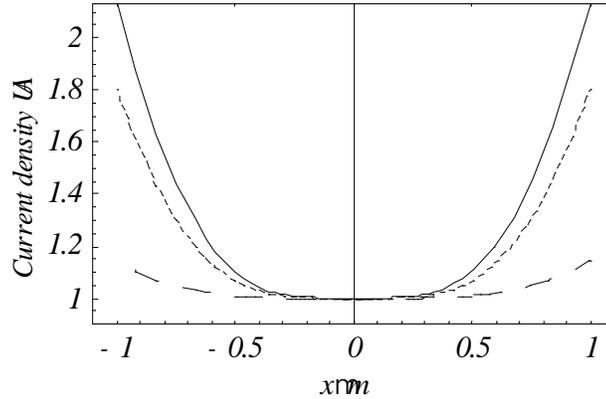


Figure 2. The current distribution along 2 micron wide NbN strip at 0.6 THz (dashed line), 1.6 THz (dotted line) and 2 THz (solid line).

Although the expression derived here for the current distribution is different from [2] the plotted curves coincide very well.

The above derivation is based on the assumption of an infinitely long strip to simplify the problem and make it possible to solve analytically. In reality the bolometer bridge is very short (0.2 micron), limited by two thick (80 nm) golden antenna pads. Since the current distribution in the thick golden antenna arms are presumably very different from what calculated above for NbN strip, one can speculate that the current distribution in the short bolometer bridge is affected by the antenna pads. Also the influence of the substrate is completely ignored in above calculation.

In order to reveal the current distribution in the whole bolometer structure an electromagnetic simulator (*QuickWave-3D*[®]) was used.

III. QuickWave-3D[®] simulated results

The first simulated structure was a simple 10 μm long, 2 μm wide and 5 nm thick NbN strip on a substrate with $\epsilon_r = 2.2$. Figure 3 shows the structure and the current density across the strip.

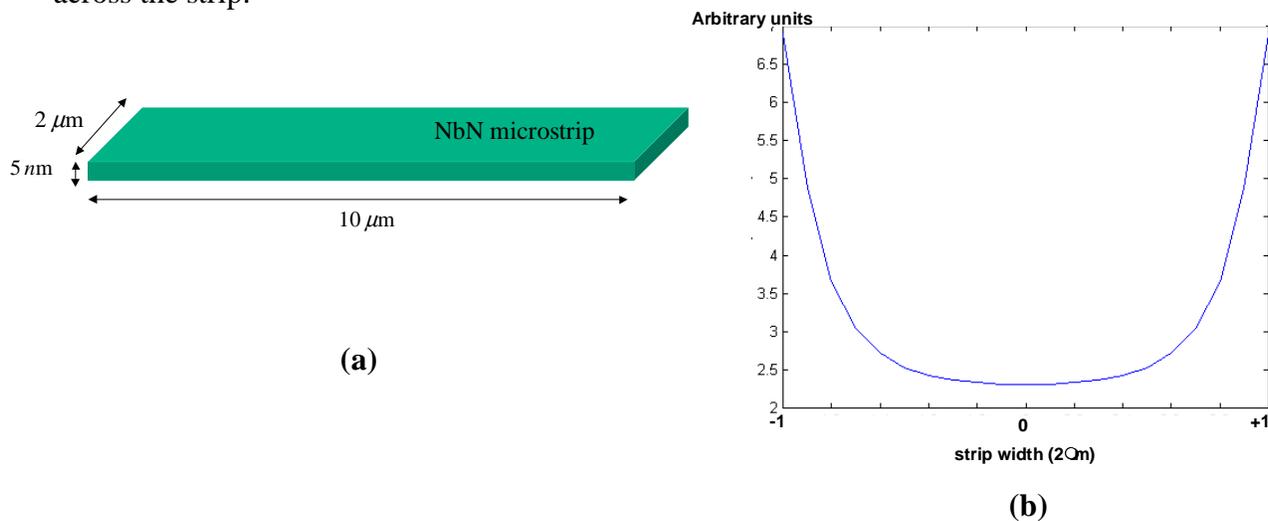
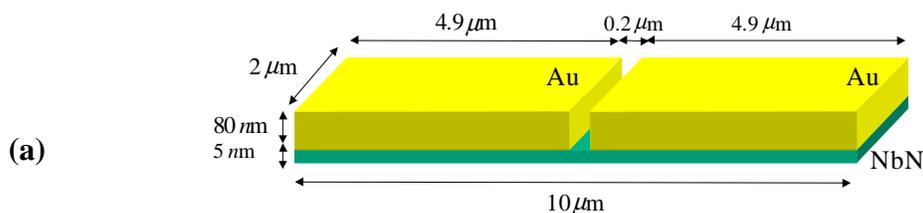


Figure 3. (a) NbN thin microstrip structure and (b) the current distribution inside NbN at 2 THz.

QuickWave-3D[®] gives the electromagnetic fields solution using Finite-Differences in Time-Domain (FDTD). Since the current density along the strip is proportional to the E field in that direction one can estimate the current density using QuickWave-3D[®].

Secondly the bolometer structure is simulated. The bolometer bridge is 0.2 μm long, 2 μm wide and 5 nm thick NbN strip. The gold pads are 80 nm thick. Figure 4 shows the schematic picture of the structure and the current density distribution inside the NbN strip under the gold pads and the gap.



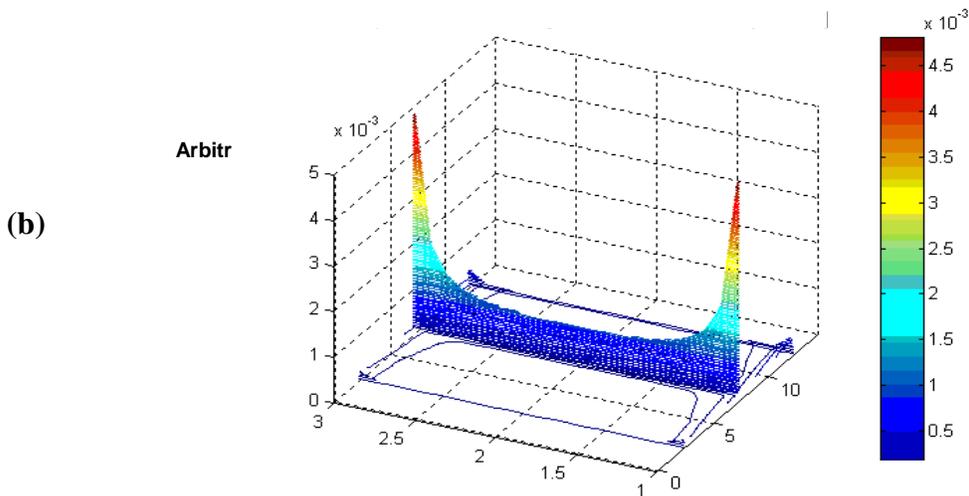


Figure 4. (a) Simulated bolometer structure and (b) the current distribution in NbN layer

The current density in NbN strip under the gold pads is almost zero. This means that almost all the RF current flows in the gold as expected. Figure 5 summarizes the simulated and analytical results. In QuickWave there is an option that applies edge singularity correction. When long strip was simulated with edge singularity option on, the current distribution was slightly different as plotted in figure 5.

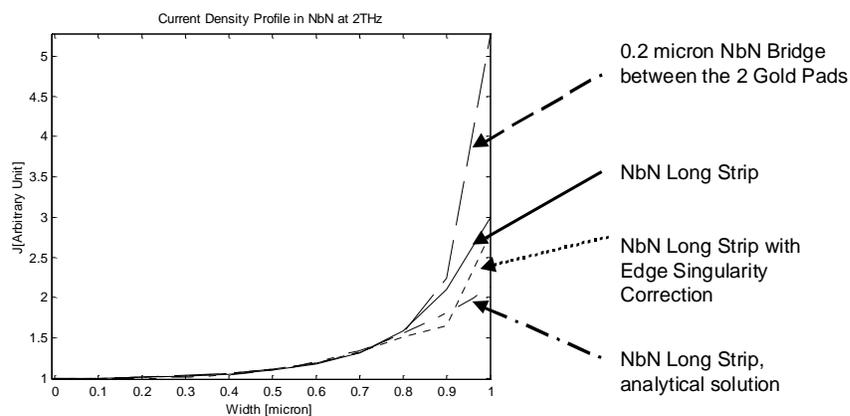


Figure 5. Simulated and analytically calculated results of RF current distribution in half of the 2 micron wide NbN strip. 0 is in the middle of strip and 1 is at the edge.

The RF current distribution in the NbN bolometer structure shows a strong non-uniformity, even more than for the long NbN strip. This is an indication that the current

distribution in the NbN bridge is clearly affected by the current distribution in the gold contacts.

IV. 2D bolometer model

In order to estimate the effect of non-uniform absorbed LO power across the bolometer bridge on the conversion loss of the device, the bolometer is divided into several parallel strips. If the number of these parallel strips is large enough the RF current distribution on each of these strips is approximately uniform. So they can be modeled by a one-dimensional hot spot model [1]. All these parallel strips share the same voltage but they have different resistance and different DC current because the absorbed LO power in each strip is different. It is also assumed that there is no lateral current in the bridge.

In order to estimate the conversion loss of such system one should first calculate the current and resistance of the device at certain bias voltage and absorbed LO power using the large signal model [1]. The absorbed LO power in each of the parallel strips depends on the LO frequency and the width of the bolometer. Knowing the absorbed LO power one can solve for the DC currents in each strip. The requirement is that the absorbed DC power together with the absorbed LO power in each strip should cause a resistance, which holds the relations:

$$R_i I_i = V \quad \text{for all } i.$$

Figure 6 shows the schematic picture of a bolometer divided into several parallel strips.

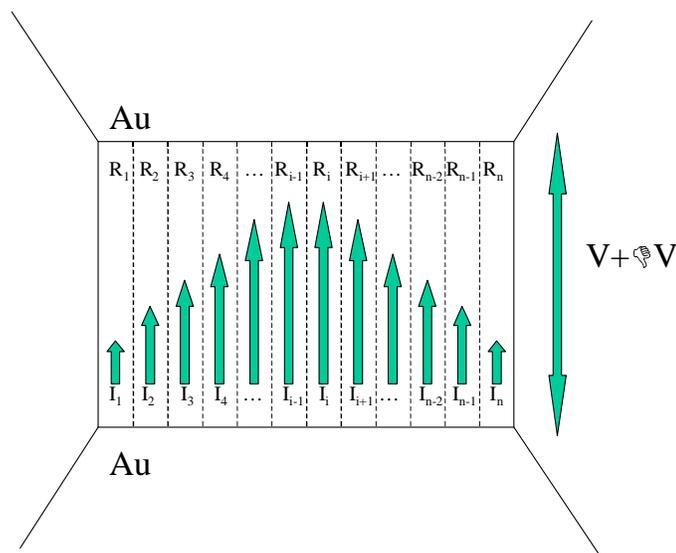


Figure 6. Schematic top view of a bolometer divided into several parallel strips.

The resistances of the middle strips are lower than of the edge strips. Therefore the DC current flows more in the middle. Consequently the size of the hotspot on the edges is larger than in the middle.

Figure 7 shows an estimated two-dimensional electron temperature profile of a bolometer around optimum operating point.

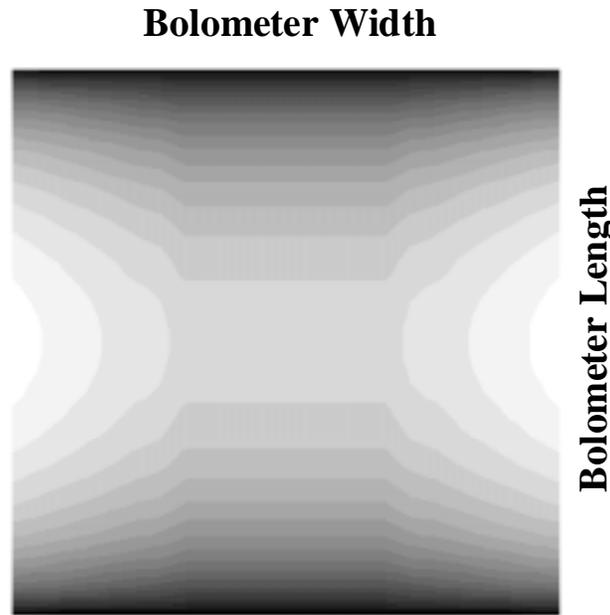


Figure 7. 2D-electron temperature profile of a bolometer. The light color stands for high temperature

Literally we can say that this is as if we have similar bolometers that are biased with the same bias voltage but different absorbed LO power.

By solving the small signal current in each of the strips using the hotspot model [1] one can estimate the conversion loss of the bolometer. Our calculation shows that due to the non-uniform RF current distribution at 2 THz the conversion loss can be up to 6 dB higher than what we calculate at 0.6 THz.

V. *Sonnet*[®] simulated results

The RF current distribution was also simulated by *Sonnet*[®], which is based on moment method. On the contrary to *QuickWave3-D*[®], it shows uniform current distribution in the bolometer bridge. Figure 8 shows the simulated result at 2 THz for a 0.2 μm long, 2 μm wide and 5 nm thick NbN bolometer.

The same uniformity was observed when simulating a long thin NbN strip. Non-uniform current was only in thick NbN strips (100 nm). *Sonnet*[®] does not show any edge singularity at frequencies lower the frequency where the resistance per unit length equals the inductive reactance per unit length [5]. In thin NbN strip where resistance is high this frequency is much higher than 2 THz and the edge singularity does not appear.

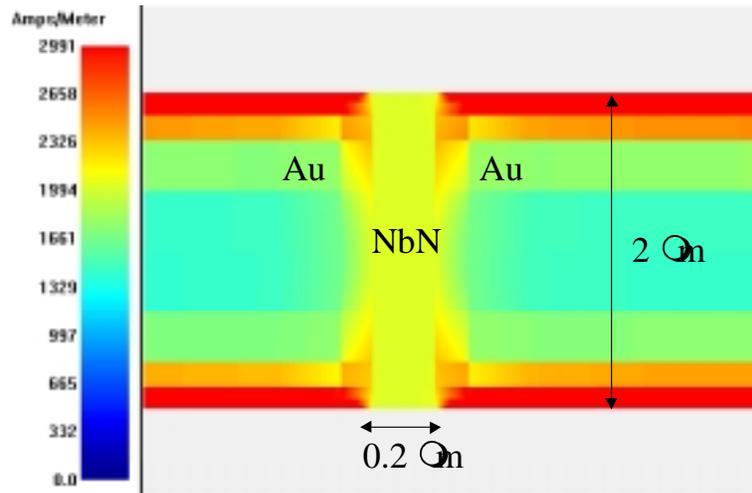


Figure 8. RF current distribution simulated by *Sonnet*[®].

VI. Discussion and conclusion

Non-uniformity in RF current distribution has a large impact on the performance of the bolometer. Our QuickWave simulated results are in agreement with analytical calculations indicating a strong non-uniform LO power absorption across the bolometer bridge at 2 THz. However *Sonnet* simulated results do not agree with that. Since QuickWave is based on FDTD 3-dimensional electromagnetic simulation and confirms the analytically calculated results the authors tend to believe in non-uniformity of RF current in the bolometer. Accordingly less degradation is expected for a device with smaller width when operating at higher frequencies, which is a subject of further investigation.

Novel designs such as thin parallel bolometer strips with different antenna pads configuration have to be investigated to achieve more uniform RF current distribution and eventually decrease the intrinsic conversion loss.

Rejecting the non-uniform current distribution, other reasons for observed increase of conversion loss by increasing the RF frequency must be found.

VII. Acknowledgements

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References

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