Superconducting Microstrip-Fed Antenna; Coupled to a Microwave Kinetic Inductance Detector

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***Abstract*— A proper antenna to couple to a microstrip Microwave Kinetic Inductance Detector (MKID) is designed and simulated. A twin-slot microstrip-fed inline antenna is designed for frequency band of 600-720~GHz integrated with an elliptical lens and coupled to the MKID. A systematic design procedure for design of such antenna with microstrip inline feeding is presented. Whole structure of lens and twin slot is simulated by full-wave electromagnetic numerical software. A locally changing technique is also used to have good matching between antenna and feed line. Results show good radiation pattern with directivity near 30dB and side lobe levels better than -10.5 dB in both H-plane and E-plan and also antenna efficiency is better than 93% and total coupling efficiency is better than 84% in whole frequency band. This antenna is recently used in a superconducting on-chip sub-millimeter wave filterbank spectrometer.**

***Index Terms*—** Microstrip-fed antenna, Microwave kinetic inductance detector, Sub-mm wave detector, Superconducting inline antenna, Twin slot antenna.

I. INTRODUCTION

Superconducting detectors have been a subject of inetense interest for detection of electromagnetic radiation in sub-milimeter and THz regimes over the last decays. Microwave Kinetic Inductance Detectors (MKIDs), which introduced recently [1], are among the most sensitive low temperature detectors available for radiation detection, especially in astronomy applications. MKID consists of a high quality superconducting resonator, whose resonant frequency is often designed at microwave range (few GHz). Quasiparticles created by incident radiation are sensed by measuring the change in the surface impedance of the resonator. Significant works have been reported on the physics and potential performance of MKIDs for astronomy applications [2]-[4]. Coupling of an antenna to a MKID improves its sensitvity considerably [5],[6]. This antenna is usually a lens antenna which fed by a suitable planar antenna. Almost all of the realized MKIDs up to now is based on Coplanar Waveguuide (CPW) structures. In [7] the microstrip MKID is realized but without the coupled antenna.

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In this work we design and full-wave electromagnetically simulated an inline-fed antenna for coupling to the MKID in microstrip structure to avoid the stray light in the substarte. This work was

an initial part of the on-going project of a new 3D optical spectrometer which use the filter bank to divide the incoming signal into separate wavelength bins [8],[9]. Hence we need microstrip structure to prevent light from bypassing the filter bank. Additionally microstrip structure in comparison by CPW structure doesn't have parasitic modes and therefore doesn't need to air bridge. Designing a proper antenna is very important for the MKID to perform well. This antenna should perfectly cover the desired frequency band of 600-720 GHz and has a good reflection and very directive radiation pattern. For this goal we choosed 8mm diameter elliptical lens antenna in combination with a twin slot antenna, which be fed by inline microstrip transmission line.

Whole structure of lens and twin slot antenna is simulated by using full wave electromagnetic software, *CST Microwave Studio* [10]. Realization of a Balun structure in the feeding line improve the antenna performance. The systematic procedure for design of twin-slot antenna with inline microstrip fed is presented in this paper.

The designed antenna has good radiation pattern with directivity near 30dB and side lobe levels better than -10.5 dB and -22 dB in H-plane and E-plan respectively and also antenna efficiency is better than 93% and total coupling efficiency is better than 84% in whole frequency band. This antenna is fabricated and used in a superconducting on-chip submilimiter wave filterbank spectrometer [9].

The organization of this paper is as follows. In section II, the design procedure of antenna is introduced. Section III presents the CST simulation results of the designed antenna.Finally, conclusions are drawn in section IV.

II. THEORY & DESIGN

Design of twin slot antenna is reported in the literatures [11]-[13] which usually fed directly by a single ended CPW line. Few works report simple kind of microstrip fed double slot antenna [14],[15]. X-Slot antenna with inline feeding is reported in [16] which principally is similar to the twin slot antenna but it is fed by a simple straight CPW line. So a systematic design procedure for inline microstrip fed antenna is necessary yet.

The twin slot antenna is patterned in a 300 nm-thick layer of superconducting NbTiN. Above this layer there is a Sapphire wafer with 350 μm thickness. Behind the antenna we place a microstrip line made of NbTiN, which is 3 μm in width and 300-nm in thickness. The thick NbTiN layer serves as the ground plane, and between the conductors, there is a 4 μm-thick layer of lossless silicon. Fig 1 shows the cross section of the multi-layer structure. We used a glue layer to stick the ground plane of NbTiN to Sapphire wafer which we considered 10 μm thickness and we supposed in the worst case it has dielectric constant of 2 which is very different with Si and Sapphire. Further information are

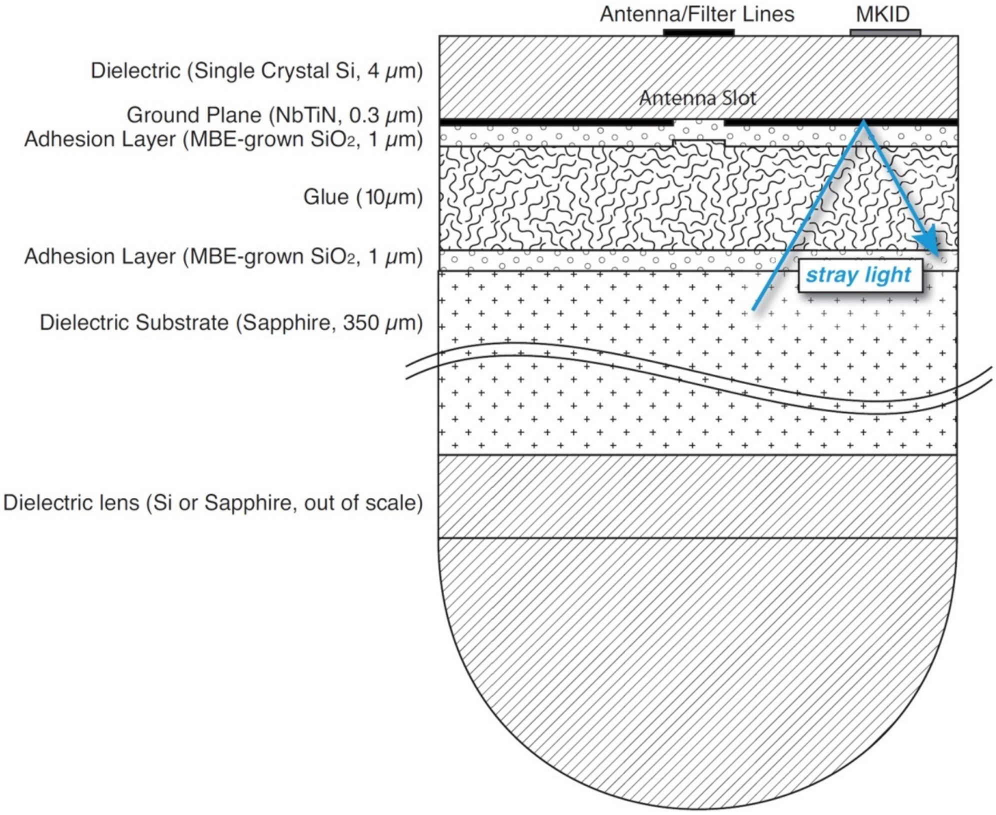


Fig 1. The cross section of the used multilayer structure. Using microstrip structure shield the MKID from the stray lights

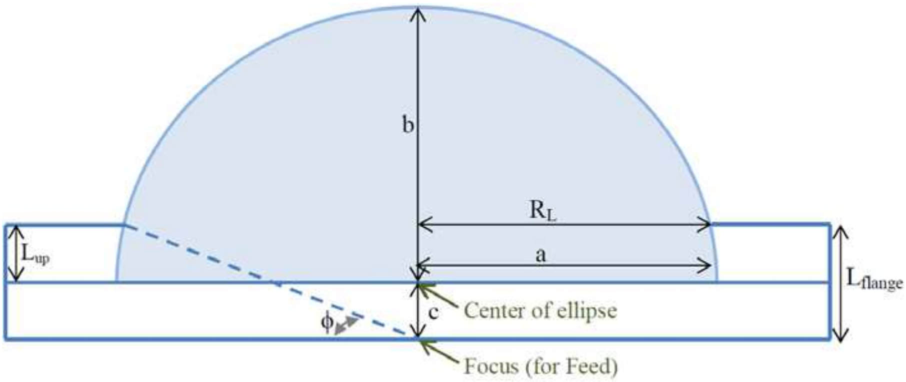


Fig 2. The general configuration of lens antenna. All dimensions are given inTable I.

reported in [8].

For the lens we consider an anti-reflection (AR) coating layer to achieve better matching. The general configuration of the antenna is shown in Fig 2. All dimensions of the lens are listed in Table I. We consider an AR layer with a thickness of 115 μm, which has a dielectric constant of 3.46.

Table I . DIMENSIONS OF THE LENS

Dimension	**Value (µm)**
Major radius of ellipse (b)	4250
Minor radius of ellipse (a)	4065
Distance of focus from center (c)	1240
Apparent radius of lens (R_L)	4000
Extra Length (L_{up})	757
Flange length (L_{flange})	1650
Edge ray angle (φ in degree)	22.5

The systematic design procedure for designing an inline microstrip-fed twin slot antenna consists of the following steps:

1. Design a 100 ohm twin slot antenna by placing a discrete face port in the balun section of the structure, without a microstrip transmission line.
2. Using a short circuited transmission line with a single 100 ohm discrete face port near the antenna to obtain the proper value for the microstrip line width.
3. Using a microstrip line with two anti-parallel 50ohm discrete face ports near the antenna to obtain the finalized width and length of the balun section.
4. Using two short 50 ohm microstrip transmission lines with two internal waveguide ports.
5. Realizing the final structure by tapering the balun section and considering two waveguide ports at two ends.

Now we explain each step in details.

Step 1; Using a discrete face port:

At first we should design a directly fed twin slot antenna which has the proper impedance. Feeding directly means using a 100 ohm *discrete face port* (The *discrete face port* will be created between the two selected edges) at the middle of the antenna structure. This port should be an *discrete face port* to decrease undesired parasitic effects.

With regard to feeding the antenna with a 50 ohm half-wavelength resonator, in the final structure, the antenna impedance should be 100 ohm. In other words, we have an inline antenna structure, which observes two 50 ohm lines in series on both sides. Hence for good matching the antenna impedance should be 100 ohm. The equivalent circuit for the inline microstrip fed antenna is shown in Fig 3.

As can be seen in the previous figure, we should realize a balun structure (balanced to unbalance converter) to convert the unbalanced (single-ended) circuit of the antenna to a balanced structure (differential circuit) of the aluminum transmission lines. To have a good matching the antenna impedance should be twice of the line impedance and so the winding ratio of 'n' should be equal to 1.

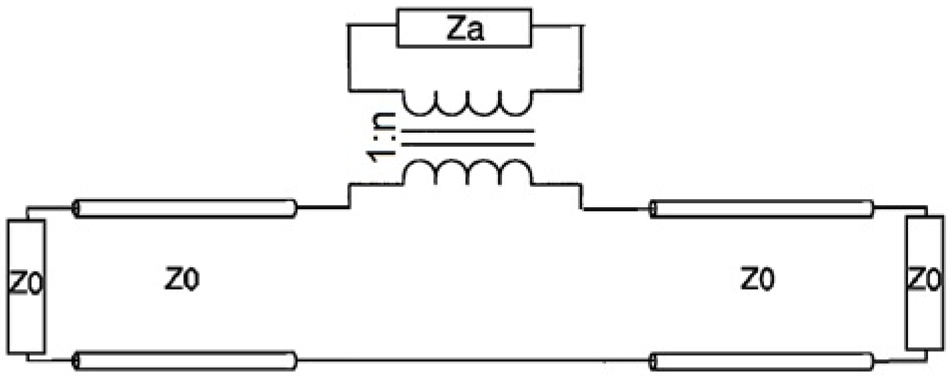


Fig 3. The equivalent circuit for the antenna. Z_a shows the antenna impedance which is coupled to an inline microstrip feeding. Coupling between antenna and feeding line is modeled by a transformer. Perfect matching is occurred when the antenna impedance be twice of

We should achieve this goal with design of the length and width of transmission line of bulun section (locally changing). By optimizing the design, the real part of the impedance of the antenna in the desired frequency band should be around 100 ohm and the imaginary part of impedance also is desired to be zero.

Step 2; Short circuit with via hole:

In this step we want to determine the proper width of the stripline in the vicinity of the antenna, which should act as an impedance transformer for good matching. We used a 100 ohm discrete face port and a very narrow cylindrical via hole in the structure

Step 3; Two anti-parallel *discrete face ports*

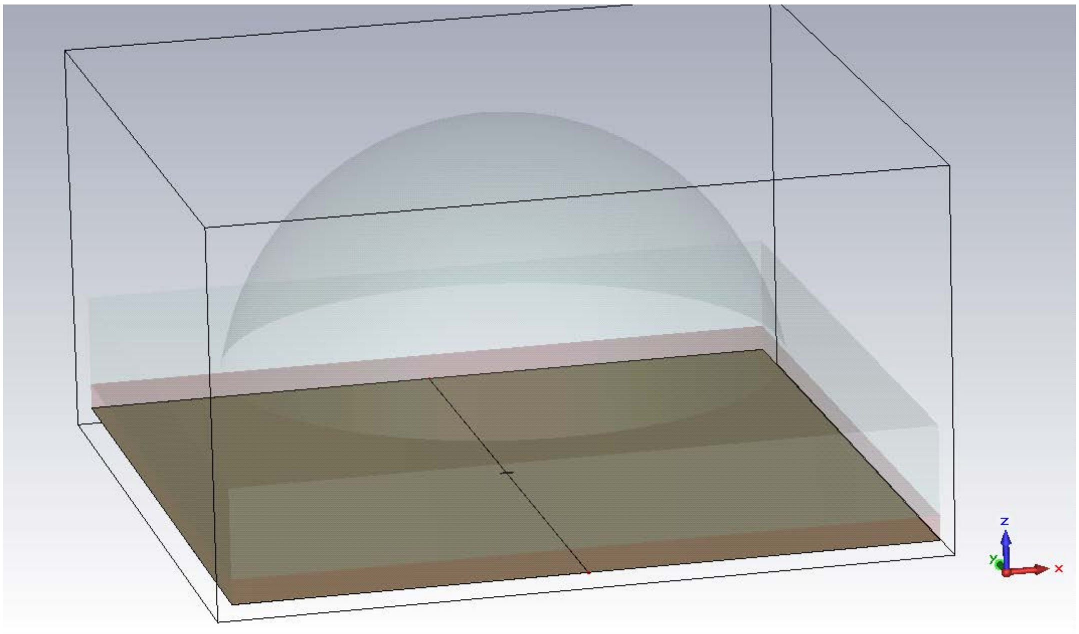
The next step is using two simultaneously excited anti-phase signals, which in this step we realized by using two anti-parallel 50 ohm *discrete face ports*. In this step we should determine the suitable value for the length of the balun section.

Step 4; Two internal waveguide ports with simultaneous anti-phase excitations:

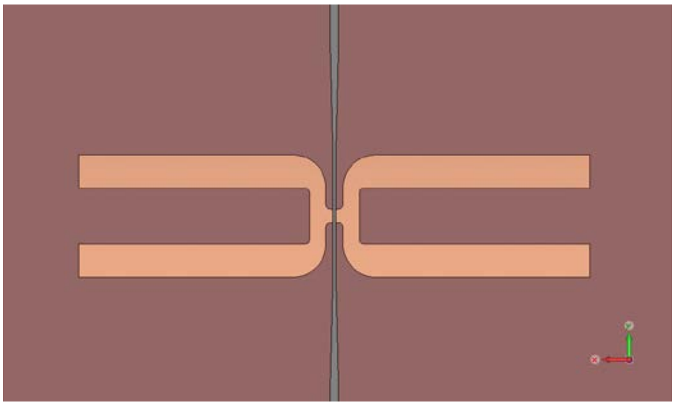
The forth step should be done by using two internal waveguide ports near the structure. In this step we determine the length of balun section transmission line. Additionally we optimize the structure.

Step 5; Final structure:

Finally we should consider two waveguide ports at the two ends, and we should also use a tapered



(a)



(b)

Fig 4. a) The complete configuration of the antenna in the schematic environment of *CST Microwave Studio,* b) The twin slot antenna structure with the microstrip feed and balun section. All dimensions which is shown in the figure are given in Table II.

line between the feed lines and the balun section as shown in Fig 4-a. Fig 4-b shows the twin slot antenna and the microstrip feed line with balun section in the antenna structure. All dimension of this figure is given in Table II. We used blended corners in the antenna structure which is easier for fabrication of antenna and also better reflection is obtained with rounded corners.

Table II . DIMENSIONS OF THE DESIGNED ANTENNA

Dimension	Value (μm)
L_1	5
L_2	44
L_3	184
L_m	42
L_t	42
W_1	6
W_2	18
W_3	12
W_m	1
W_f	3
R_1	12
R_2	1.5

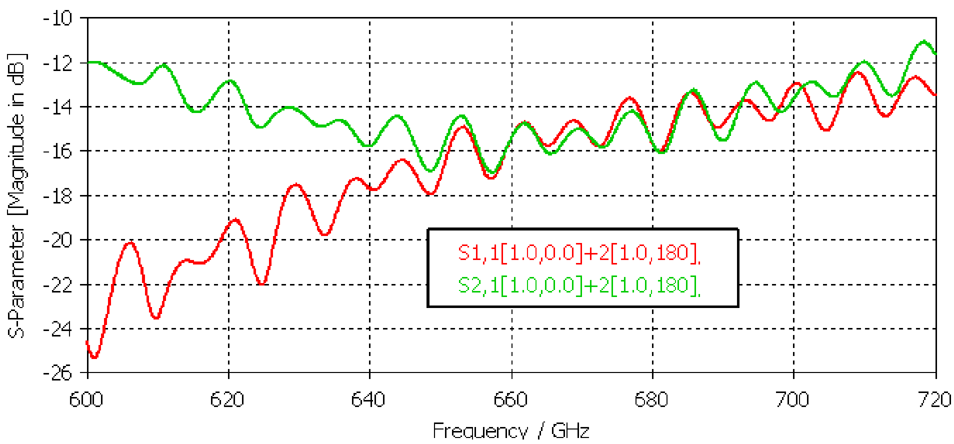


Fig. 5. Amount of reflection in each port for the designed antenna structure.

III. SIMULATION RESULTS AND DISCUSSION

We simulated whole structure by CST Microwave software. For feeding of this inline antenna we used simultaneously excitations with 180 degree difference in phase. Meshing of such structure is very important to have accurate results in the fastest way. In the case of simultaneous excitation several ports are stimulated at once, so it is different with the general usual S-Parameter definition. In this case the incident and reflected spectra, all normalized to the spectrum of the reference signal. Fig 5 shows the S-parameters in the final structure which shows reflection at the two ports.

Now, for the correct way of defining the antenna efficiency (e_a) in this case of simultaneous excitation, we consider the following procedure. If the radiation is considered as a third port we have:

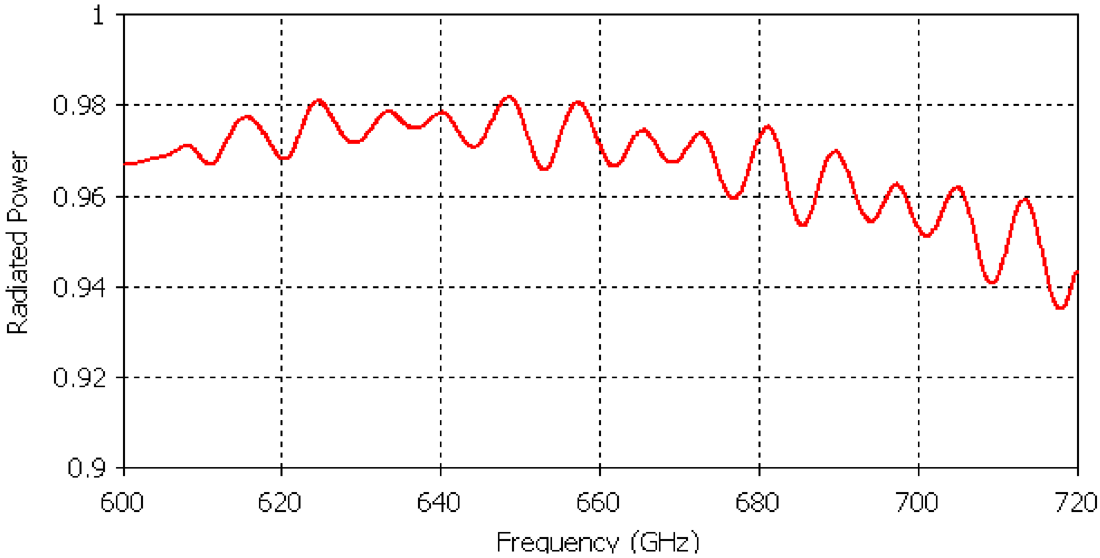


Fig. 6. Amount of calculated normalized radiated power for the designed antenna based on eq. (2).

$$|S_{1,1+2}|^2 + |S_{2,1+2}|^2 + |S_{3,1+2}|^2 = 2 \quad (1)$$

where in eq.(1) $S_{1,1+2}$ and $S_{2,1+2}$ show the reflected amplitude from simultaneously anti-parallel excitation to port 1 and port 2 respectively and $S_{3,1+2}$ shows the transmitted amplitude. Because there are two input signals, the reference signal considered in the calculation of this kind of S-parameters is twice the normal case. Therefore $|S_{3,1+2}|^2$ is in fact twice of the normalized radiated power in the normal case. Hence after normalization:

$$e_a = \frac{2-|S_{1,1+2}|^2-|S_{2,1+2}|^2}{2} = 1 - \frac{|S_{1,1+2}|^2}{2} - \frac{|S_{2,1+2}|^2}{2} \quad (2)$$

Fig 6 shows the amount of the normalized radiated power based on eq. (2). We see that the antenna efficiency is better than 93% at whole frequency band.

3D radiation pattern of the designed antenna at the center frequency of 660GHz is displayed in Fig 7. The amount of the side lobe levels in both H-plan and E-plan are shown in Fig 8-a. As can be seen in this figure the side lobe level in H-plan and E-plane are better than -10.5 dB and -22dB respectively. Additionally the directivity of antenna in the different frequencies is shown in Fig 8-b.

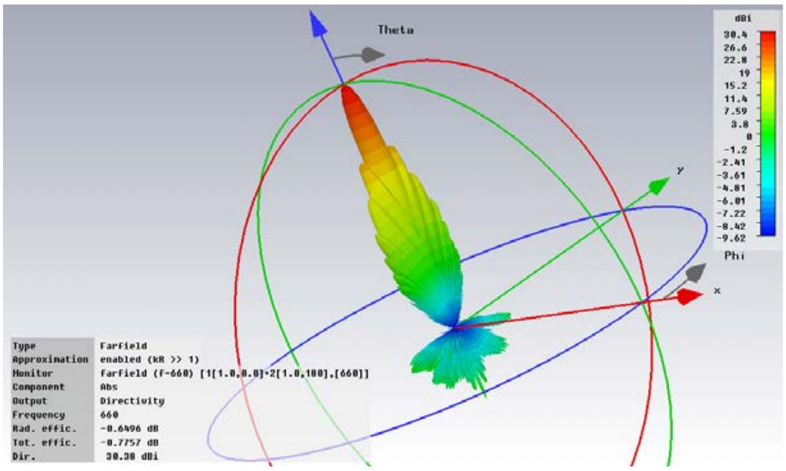
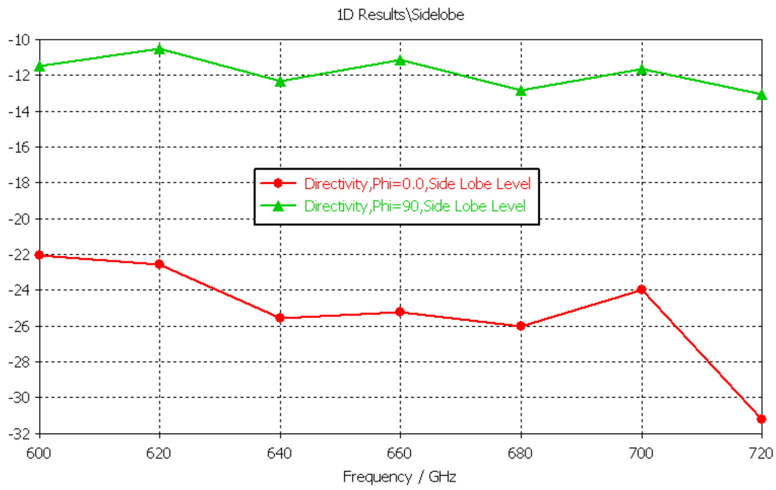
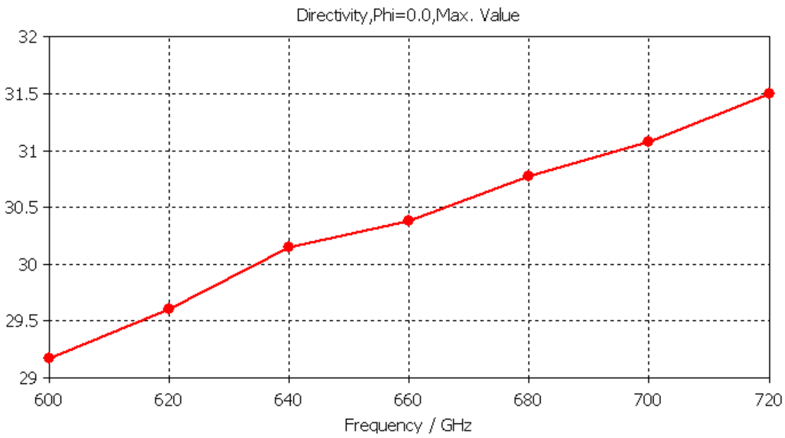


Fig. 7. 3D radiation pattern of the designed antenna at center frequency of 660 GHz.



(a)



(b)

Fig. 8. a) Amount of side lobe levels for the designed antenna structure in both H-plan and E-plan. As we expected in E-plan side lobe level is very good and in H-plan the side lobe level is better than -10.5~dB which it is good. b) Amount of directivity for the designed antenna structure in whole frequency band. Because of using a large Lens antenna the directivity is very high which we need it.

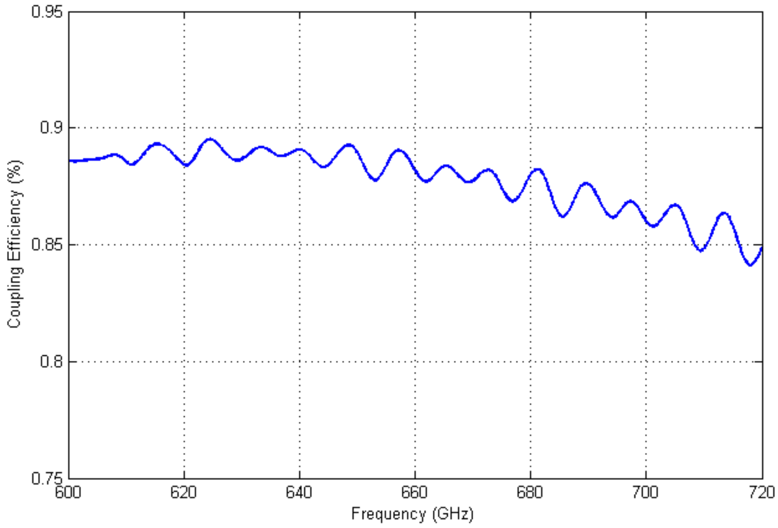


Fig. 9. The total coupling efficiency of the antenna, which is better than 84%.

To analyze the effect of the side lobes better, we calculate $\Lambda(\theta_0)$, which is the fraction of the power radiated in a solid angle of $\Lambda(\theta_0) = 2\theta_0 \times 2\theta_0$ to the total radiated power in 4 steradian (θ_0 in radian and Ω_0 in steradian). Hence if $U(\theta,\varphi)$ shows the radiation intensity, we have:

$$\Lambda(\theta_0) \ = \frac{\oiint_{\Omega_0} U(\theta,\varphi)\, d\Omega}{\oiint_{4\pi} U(\theta,\varphi)\, d\Omega} = \frac{\int_0^{2\pi}\int_0^{\theta_0} U(\theta,\varphi)\, sin\theta\ d\theta d\varphi}{\int_0^{2\pi}\int_0^{\pi} U(\theta,\varphi)\, sin\theta\ d\theta d\varphi} \tag{3}$$

where $U(\theta,\varphi)$ is the radiation intensity in a given direction is defined as the power radiated from an antenna per unit solid angle. Therefore in each frequency we can determine the amount of power in the main lone ratio to total radiated power which it is called "beam efficiency". And finally the total coupling efficiency of antenna is obtained by multiplying of the antenna efficiency and beam efficiency. Fig 9 displays the total beam efficiency of the designed antenna at the total frequency band of 600-720 GHz.

IV. CONCLUSION

An inline microstrip-fed twin slot antenna in combination with an elliptical Si lens for coupling to a microstrip MKID is presented. Using balun section leads to good matching between antenna and feed line. Whole structure si simulated by electromagnetic full-wave simulator of CST. The designed antenna has very good reflection and its power radiation pattern shows side lobe levels better than -10.5 dB in both H-plan and E-plan and beam efficiency is good enough. Total efficiency of more the 84% is obtained in whole frequency band of 600-720 GHz. This antenna is used in a superconducting on-chip sub-millimeter wave spectrometer.

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REFERENCES

[1] P.K. Day, H.G. LeDuc, B.A. Mazin, A. Vayonakis, and J. Zmuidzinas, "A broadband superconducting detector suitable for use in large arrays," NATURE, 425(6960), pp. 817–821, Oct. 23 2003.

[2] Y. Lankwarden, A. Endo, J. Baselmans, and M. Bruijn, "Development of NbTiN-al direct antenna coupled kinetic inductance detectors," Journal of Low Temperature Physics, 167, pp. 367–372, 2012.

[3] S. Doyle, P. Mauskopf, J. Naylon, A. Porch, and C. Duncombe, "Lumped element kinetic inductance detectors," Journal of Low Temperature Physics, 151, pp. 530–536, 2008. 10.1007/s10909-007-9685-2.

[4] Monfardini, A., Swenson, L. J., Bideaud, A., D´esert, F. X., Yates, S. J. C., Benoit, A., Baryshev, A. M., Baselmans, J. J. A., Doyle, S., Klein, B., Roesch, M., Tucker, C., Ade, P., Calvo, M., Camus, P., Giordano, C., Guesten, R., Hoffmann, C., Leclercq, S., Mauskopf, P., and Schuster, K. F. Nika, A millimeter-wave kinetic inductance camera. A & A, 521:A29, 2010.

[5] P. Diener, H. Leduc, S. Yates, Y. Lankwarden, and J. Baselmans, "Design and testing of kinetic inductance detectors made of titanium nitride," Journal of Low Temperature Physics, 167, pp. 305–310, 2012.

[6] A. Baryshev, J.J.A. Baselmans, A. Freni, G. Gerini, H. Hoevers, A. Iacono, and A. Neto, " Progress in antenna coupled kinetic inductance detectors," Terahertz Science and Technology, IEEE Transactions on, vol. 1, no. 1, pp. 112 –123, Sept. 2011.

[7] Benjamin A. Mazin, Daniel Sank, Sean McHugh, Erik A. Lucero, Andrew Merrill, Jiansong Gao, David Pappas, David Moore, and Jonas Zmuidzinas, "Thin film dielectric microstrip kinetic inductance detectors," Applied Physics Letters, 96(10):102504, 2010.

[8] A. Endo, J. J. A. Baselmans, P. P. van der Werf, B. Knoors, S. M. H. Javadzadeh, S. J. C. Yates, D. J. Thoen, L. Ferrari, A. M. Baryshev, Y. J. Y. Lankwarden, P. J. de Visser, R. M. J. Janssen, and T. M. Klapwijk,"Development of deshima: a redshift machine based on a superconducting on-chip filterbank," Proc. SPIE 8452, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI, pages 84520X–84520X–15, 2012.

[9] A. Endo, C. Sfiligoj, S.J.C Yates, J.J.A. Baselmans, D.J. Thoen, S.M.H. Javadzadeh, P.P. Van der Werf, A.M. Baryshev, and T.M. Klapwijk, "On-chip filter bank spectroscopy at 600–700 GHz using NBTIN superconducting resonators," Applied Physics Letters, 103(3):032601, 2013.

[10] CST Microwave Studio 2012. www.cst.com.

[11] P. Focardi, W.R. McGrath, and A. Neto, "Design guidelines for terahertz mixers and detectors," Microwave Theory and Techniques, IEEE Transactions on, 53(5), pp.1653 – 1661, May 2005.

[12] Chi-Hsuan Lee, Shih-Yuan Chen, and Powen Hsu, "Efficiency-enhanced and size-reduced coupled twin slots capacitively fed by conductor backed coplanar waveguide,"Antennas and Wireless Propagation Letters, IEEE, 8: pp. 1033 –1035, 2009.

[13] D.F. Filipovic, S.S. Gearhart, and G.M. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," Microwave Theory and Techniques, IEEE Transactions on, 41(10), pp. 1738 –1749, Oct. 1993.

[14] R.L. Rogers, S.M. Wentworth, D.P. Neikirk, and T. Itoh,"A twin slot antenna on a layered substrate coupled to a microstrip feed line," International Journal of Infrared and Millimeter Waves, 11, pp. 1225–1249, 1990.

[15] J. Zmuidzinas and H.G. LeDuc, "Quasi-optical slot antenna sis mixers," Microwave Theory and Techniques, IEEE Transactions on, 40(9), pp. 1797 –1804, Sep. 1992.

[16] A. Iacono, A. Freni, A. Neto, and G. Gerini, "In-line x-slot element focal plane array of kinetic inductance detectors," Antennas and Propagation (EUCAP), Proceedings of the 5th European Conference on, pp. 3316 –3320, April 2011.