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TLS Noise Reduction and Sensitivity Improvement of the Microwave Kinetic Inductance Detectors

A. Ali Farivar[1] and S. Mohammad Hassan Javadzadeh[1*]
Electrical & Electronic Engineering Dept., Shahed University, Persian Gulf Highway, Tehran, Iran,
a.farivar@shahed.ac.ir, Smh.javadzadeh@shahed.ac.ir
Corresponding author: Smh.javadzadeh@shahed.ac.ir

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Abstract-In this paper, we report the sensitivity of superconducting detector resonators and shows which kind of detector is appropriate for detecting cosmic microwave background (CMB). Photons absorbed from galaxies have information about dark matter and dark energy and we need advanced technology to observe cosmic rays. Microwave kinetic inductance detectors (MKIDs) can be used to enjoy an array of thousands of pixels, and a small size design. Sensitive MKIDs with little quantity of noise equivalent power (NEP) could detect photons that have very low energy but intrinsic noise particularly TLS noise. How to design an MKID based on decreasing TLS noise is discussed here. This transmission line resonator was designed with an open circuit lambda second waveguide. This MKID has a reliable quality factor in 6 GHz frequency. An array that includes 8 MKIDs has been designed. The responses which were taken prove that the sensitivity of these MKIDs compare to former MKIDs is slightly more valid.

Index Terms- Microwave kinetic inductance detectors (MKIDs), Lumped element kinetic inductance detectors (LeKID), Noise equivalent power (NEP), Two-level system (TLS) noise and Sensitivity of resonator.

I. INTRODUCTION

Cosmic Microwave Background (CMB) has most of the information about the Big Bang, early galaxies, and unknown phenomenon such as dark matter, dark energy, and black holes. Kinetic inductance detectors (KIDs) which absorb photons from different sources in the galaxy and cosmic microwave background (CMB) are used for cosmic imaging from clusters and nebulae. With Kinetic inductance in superconductors, resonators could be designed to detect optical, sub-millimeter, and X-ray waves in microwave bandwidth.

Having a look at different detectors and their specifications could highlight the advantages of Microwave Kinetic Inductance Detector.

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A. Conventional Bolometers

Bolometers are a kind of detector that can detect cosmic rays by measuring resistance changes. When photons are absorbed in the thermistor which is into the detector, the temperature of it changes and the resistance changes consequently. Bolometers could detect millimeter and sub-millimeter rays [1].

B. Magnetic Microcalorimeters

Magnetic microcalorimeters (MMCs) work similarly to the previously mentioned detector. There is a small strip on MMCs that can measure resistance changes. The resistance changes happened due to changing magnetic fields in the small strip after photons or rays have been absorbed [2].

Superconductors are used in three kinds of low-temperature detectors which are explained. Each superconductor has its own critical temperature under which the electrons are coupled with each other and Cooper pairs are created. Photons that have been absorbed in a superconductor can break Cooper pairs and then quasiparticles are created [3].

C. Transition Edge Sensors

Transition edge sensors have a strip made with a superconductor. After break Cooper pairs are broken by photons that have been absorbed, and a current in the strip is created. To read out the current, an amplifier such as a superconducting quantum interference device (SQUID) is needed. Due to the current, the superconductor’s temperature increases and reaches a critical temperature. The disadvantage of this detector is that it could not use a large number of pixels. If TESs are used in a large array, each detector has to have an amplifier. Therefore, the temperature of the detector will increase [4].

D. Superconducting Tunnel Junctions

Superconducting tunnel junctions (STJs) are the next one of low-temperature detectors which consists of superconducting-normal-superconducting (SIS). Quasiparticles which are created when photons hit Cooper pairs, the tunnel between strips. This movement is called Josephson current. The readout of this current is done by a radio-frequency single-electron transistor (RF-SET). Obviously, making a strip with high quality and its maintenance is a great challenge [5]-[6].

E. Microwave Kinetic Inductance Detectors

Microwave Kinetic Inductance Detectors (MKIDs) are the last one of the low-temperature detectors we want to explain. By this technology, cosmic rays which are in Terahertz bandwidth in microwave bandwidth can be detected. The greatest advantage of this detector is kinetic inductance. When quasiparticles are created by photons, the inductance factor of the resonator will change, and then resonance happens. Another advantage is that MKID can be used in large arrays and hundreds of pixels. They have extremely high sensitivity in sub-millimetre, millimeter, optical/UV, and X-ray imaging [7]-[8].

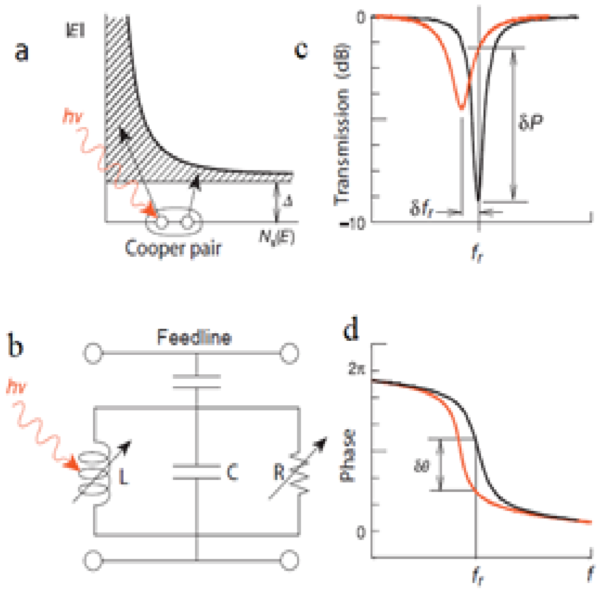

Fig. 1. Sample illustrates detection operation. (a) absorbed photon with hυ energy that is greater than Δ superconductor gap energy, (b) the change of kinetic inductance in resonator, (c) the resonance circuit has a narrow dip in resonance frequency, (d) the microwave probe signal obtains a phase shift when resonance frequency changes.

II. DETECTION PROCESS IN MKID

According to BCS theory when photons are absorbed to a superconductor with 2Δ0≈3.52kbTc and Δ0, the gap energy of the superconductor causes Cooper pairs to break and generate quasiparticles. Quasiparticles generated move to the surface of the superconductor and change kinetic inductance and surface impedance parameters of the superconductor Zs=Rs+jXs. Resistance in superconductivity is zero and due to Cooper pairs break, inductance parameter changes which is shown in Fig.1 [9]-[10].

III. INTRINSIC NOISES

When photons with high energy absorb on superconductor film, they could break the greatest number of cooper pairs leading to the creation of more quasiparticles. Some fluctuations in superconductor are due to random generation and recombination of quasiparticles. This event increases (or could increase) the temperature of the superconductor and could get as high as the critical temperature of the superconductor. Another behavior that happens in the superconductor is the tunneling junction of quasiparticles between the superconductor film and a dielectric layer. Generated most of the quasiparticles in the superconductor found two different situations in the superconductor and dielectric layer. In this case, atoms want to move to another condition (to dielectric).This causes the atoms to have less aggregation, which means the atoms have a dipole moment. This movement of atoms is found in an electric field that can be coupled to the electric field of the resonator [11]-[12].

A. Two-Level System Noise

Expected quasiparticles created move to the surface of the superconductor, but some of them gather on the bottom of the superconductor film. Based on the intrinsic behavior of charges and quasiparticles, they move to amorphous solids like a substrate or positive situation rather than superconductor film. Charges move between two different situations or tunnel between them. This fluctuation is Two-Level System (TLS) noise, and TLS noise affects the quality factor and frequency response of the resonator. The TLS noise that exists in the resonator can decrease the quality factor and shift resonance frequency. This inner loss of the resonator with 1/QiTLS ratio can be calculated by [13].

$$\frac{1}{Q_i^{TLS}} = \frac{\int_{Vh} Im\{\epsilon TLS\}|\underset{E}{\rightarrow}\left(\underset{r}{\rightarrow}\right)|\hat{}2\underset{dr}{\rightarrow}}{\int_V \epsilon|\underset{E}{\rightarrow}\left(\underset{r}{\rightarrow}\right)|\hat{}2\underset{dr}{\rightarrow}} \tag{1}$$

On the other hand, frequency shift due to field of TLS noise coupled to the resonator's electric field and make fault shift resonance frequency, because with crosstalk method made frequency shift, but frequency shift due to TLS noise is undesirable frequency shift and can calculate by [14].

$$\frac{\Delta fr}{fr} = \frac{fr(T)-fr(T-0)}{fr} = \frac{F_{TLS}\delta_0}{\pi}[Re\psi\left(\frac{1}{2}+\frac{1}{2\pi i}\frac{hf}{k_BT}\right) - ln\frac{hf}{k_BT}] \tag{2}$$

Where Ψ is the complex digamma function and negligible power dependence. Filling factor F(TLS) is the ratio electric energy stored in the TLS hosting volume ωhe rather than the total electric energy stored in resonator ωe [15],16].

$$F_{TLS} = \frac{\int_V \underset{E}{\rightarrow}\left(\underset{r}{\rightarrow}\right)\underset{dr}{\rightarrow}}{\int_V \epsilon\underset{E}{\rightarrow}\left(\underset{r}{\rightarrow}\right)\underset{dr}{\rightarrow}} = \frac{\omega_h^e}{\omega^e} \tag{3}$$

And inner loss of the resonator can be rewritten as

$$\frac{1}{Q_i^{TLS}} = F_{TLS}\delta_0 \tanh(\frac{hf}{2k_BT}) \tag{4}$$

B. Fano Noise

During resonance procedure for an optical, UV, and X-ray pulse create numbers of quasiparticles due to photon absorption, and collective excitation happens. This event is phonon and most quasiparticles join the electrical field of TLS. The statistics number of quasi particles created is the Fano limit. After a while, quasiparticles join together and recombine into Cooper pairs. Generation and recombination of quasiparticles increase the temperature of the superconductor which leads to a critical temperature of the superconductor and causes figure noise and loss in the superconductor. The Fano limit is calculated by

$$\sigma_N = \sqrt{F\eta h\upsilon} \qquad (5)$$

F is Fano factor and for efficiency of quasiparticles created η=0.75. hυ is energy of incident photon and Δ is the energy gap of superconductor [17].

IV. SENSITIVITY OF KINETIC INDUCTANCE DETECTOR

In a photon detector, the minimum power of photon, able to detect is Noise Equivalent Power (NEP) of photon detector resonator. In the resonator, the power of generation and recombination is given by [18]

$$NEP_{g-r}^2 = 2[N_{th}(\tau_{max}^{-1} + \tau_{th}^{-1}) + N_{qp}(\tau_{max}^{-1} + \tau_{th}^{-1})](\frac{\Delta_0}{\eta_0})^3 \qquad (6)$$

Nth is number of thermal quasi particles and Nqp is the number of quasiparticles created. Because the frequencies of noise are negative and positive, factor 2 is added for single sided. The calculation of is prolonged we can use the estimation of the recombination NEP as [18]

$$NEP_r \approx 2\sqrt{\frac{P_0\Delta_0}{\eta_0}} \qquad (7)$$

Photons absorbed into the superconductor similar to other particles have noise equivalent power and can be calculated by [19]

$$NEP_{ph}^2 = 2P_0 h\upsilon(1 + n_0) \qquad (8)$$

Again, factor 2 is for single sided calculation, n0=1/(eh$\upsilon/kBT - 1$) and υ is photon frequency.

Above all, noise equivalent power NEPTLS is the main, because in a sensitive detector, it can disrupt the detection process and reveal wrong points. NEPTLS is calculated by

$$NEP_{ph}^2 = \frac{2S_{TLS}}{R_x^2} = 2(\frac{4N_0\Delta_0^2V}{\alpha\eta_0S_0(\omega)\tau_{qp}})^2S_{TLS} \qquad (9)$$

If one of detecting going to be accurate when unequal formulation should be $NEPTLS \leq NEPp$h a

$$NEP_{TLS}^2 = 2(\frac{4N_0\Delta_0^2V}{\alpha\eta_0S_0(\omega)\tau_{qp}})^2S_{TLS} < 2P_0h\upsilon(1 + n_0)NEP_{ph}^2 \qquad (10)$$

After rearranging we have [20]

$$S_{TLS} < \frac{h\upsilon(1+n_0)S^2(\omega)^2\tau_0\eta_0}{8\Delta_0^2F^3N_0V} \qquad (11)$$

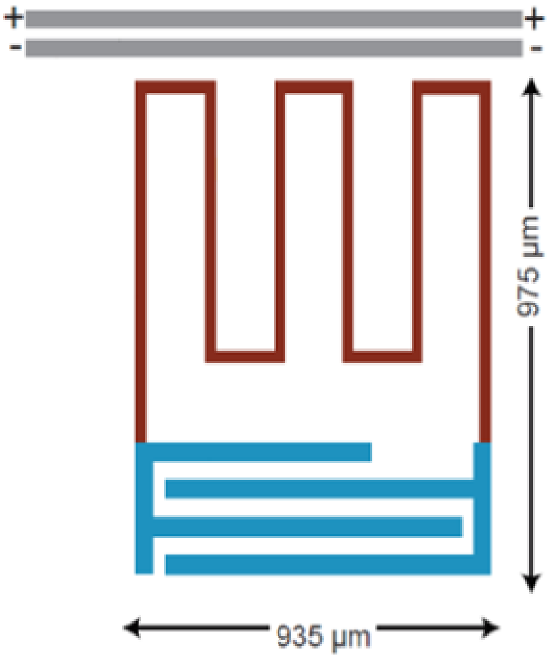

Fig. 2. The first design is LeKID resonator on sapphire substrate with λ/4 length [23].

In the above equation, the factor of α=Lki/L is the kinetic inductance fraction and contain two parts Lki to total L, and total L is Lki+Lg that stores energy in two different figures, Lg is a port of the resonator same as meander can stored energy, but Lki stored kinetic energy on field exist between waveguide and ground plain [21].

V. LUMPED-ELEMENT KINETIC INDUCTANCE

Based on decreasing intrinsic noise on MKIDs, a hybrid design is presented, because TLS happens on the coupler more than another part of the resonator because the density of perturbation happens on a region close to the feed line, and for this part of the resonator, use integrated capacitor (IDC) design. Exponentially, IDC decreases TLS noise on the coupler of the resonator and the meander design is added to IDC part and makes Lumped Element Kinetic Inductance Detector (LeKID). For analytical design of inductor and capacitor lumped element resonator approximately with the two equations bellow [22]

$$C = \varepsilon_0(1 + \varepsilon_r)N_{cap}S_{cap} \tag{12}$$

$$L = \frac{\mu_0}{2}N_{ind}S_{ind} \tag{13}$$

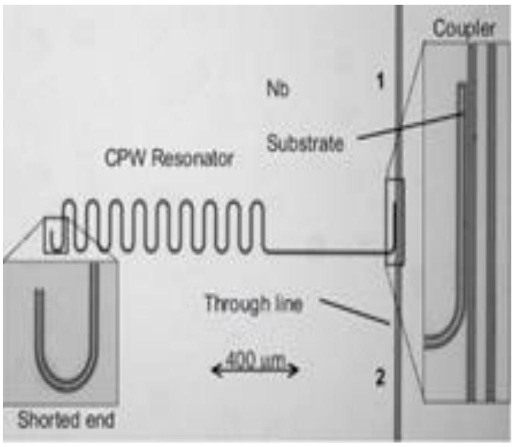

Fig. 3. The second design is an MKID resonator on silicon substrate with λ/4 length [24].

VI. COMPARISON OF DESIGNS

Detecting cosmic waves needs a design detector on nanometer-scale but with MKIDs, we are able to detect the Terahertz frequency of galaxies in the microwave range. In this section, three deference designs of MKIDs are compared in terms of the length of the resonator, kind of waveguide and quality factor of resonance.

A. First design

The first design is introduced in the resonance frequency of 1.5 GHz. This LeKID resonator is a λ/4 short circuit with CPW waveguide. The total size of the resonator is 935µm × 975µm with L=60nH and the quality factor of the resonator is 1.7×107. Fig. 2 shows this design [23].

B. Second design

Fig. 3 shows the second resonator with Lg = 0.44µH, C~0.16pF in resonance frequency of 10GHz. The quality factor of this MKID is 105 and similar to the first resonator is a λ/4 short circuit with CPW waveguide in approximately1600µm × 400µm [24].

C. Third design

The last design is a LeKID from microstrip line in λ/2 length with C = 3.91pF and L = 161µH at resonance frequency of 6GHz. This resonator is a λ/2 open circuit with a total size of 600µm×370µm on sapphire substrate. Coupler of resonator with 12 fingers IDC and other part of resonator is meander design, quality factor at 6GHz is 2.62×108 which is shown in Fig. 4.

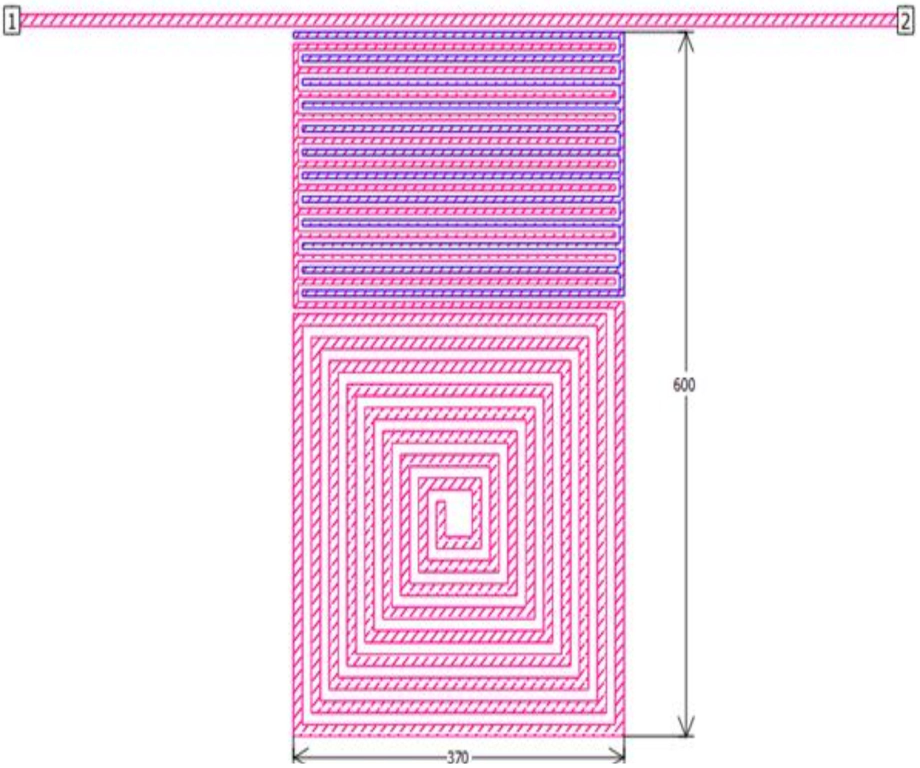

Fig. 4. The third design is LeKID and designed with SONNET software resonator on sapphire substrate with λ/2 length

Based on significant study have been done to determine the loss in amorphous materials by Omid Noroozian's PhD thesis work [25] and equation (1) that was calculated and the numerical response loss into the resonator 1/Q_i^TLS ≈ 2.80×10-12 .

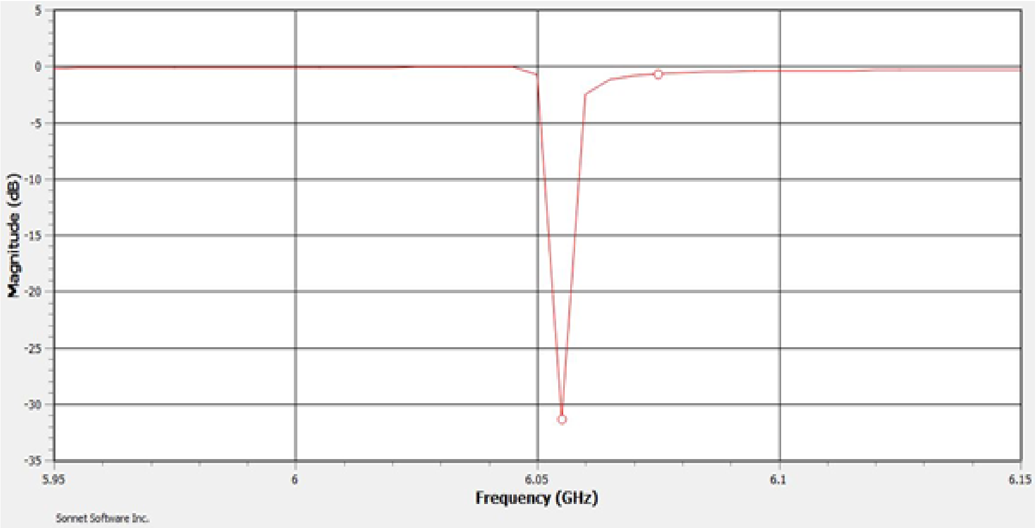

Fig. 5. The resonance frequency of the third design is LeKID and designed with SONNET software resonator on sapphire substrate with λ/2 length

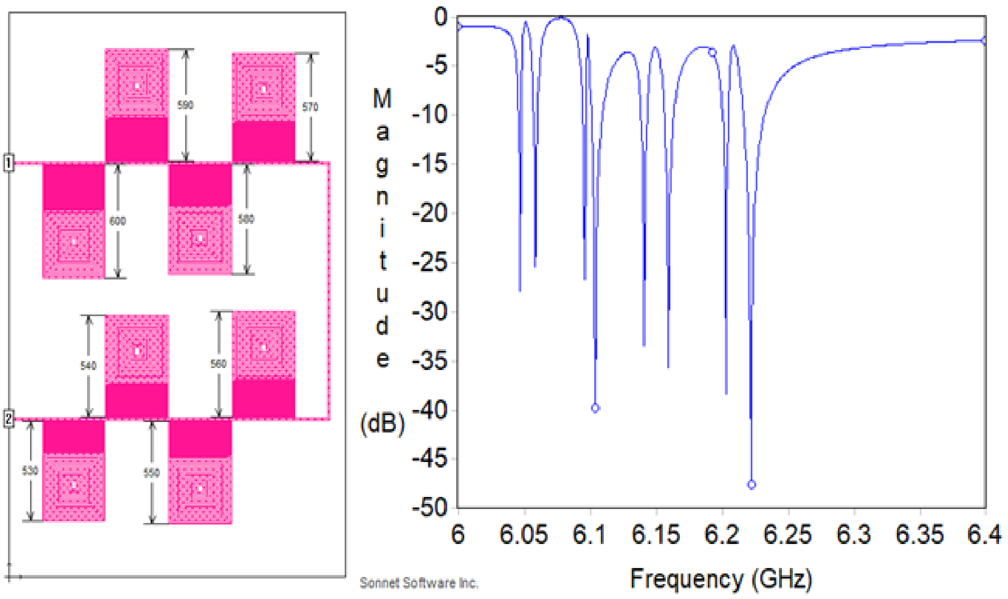

Fig. 6. The final array with frequency response by third design.
(a)Eight arrays of resonators, (b) Resonance frequency of eight arrays.

Table I. The structure of resonators with resonance frequency and the quality factor.

Number of Resonator	Ref.	Substrate Material	Inductor Type	Resonance Frequency (GHz)	Q Factor
1	[26]	Sapphire	Meander	2	3E+7
2	[27]	Silicon	Meander	6	1E+6
3	[28]	Silicon	Meander	3	5E+4
4	[29]	Silicon	Proposed Inductor	5.3	8.9E+6
5	This Work	Sapphire	Spiral	6	2.62E+8

VII. CONCLUSION

As we mentioned in the TLS section, the coupler of a resonator with IDC design potentially decreases TLS noise in the resonator and we can see this kind of coupler in the first and third designs. The main advantage of this work is the microstrip line waveguide because the microstrip line is one of the most popular waveguides that can be fabricated by photolithographic processes and miniaturized not only with both passive and active microwave devices but also can support TEM mode. Fabrication of CWP rather than microstrip line is expensive and the price for a large array is high. coupling from the feedline to the microstrip line happens better because in the CPW, the ground is plain between the main waveguide and feedlines. Most of the MKIDs designed by CPW, compared with the third design, have a microstrip line, but they do not have a Q factor as other designs. In the last design resonator with λ/2 length microstrip line waveguide. This design is different from the first and second designs in length and kind of waveguide but has an acceptable answer in quality factor resonance frequency based on the resonator loss from TLS was reported, and with meander part of the resonator can directly optical loaded and absorb photons in a large array. Fig. 5 shows a single resonator resonance frequency. The quality factor of this design is shown in Table I. This array is designed in 6-7 GHz for detecting in 600-700 GHz cosmic bandwidth. Based on simulations, we obtain great answers of high Q-factor by very low losses of TLSinto 600-700 GHz bandwidth.

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