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Date: 2025-07-24T16:58:11+00:00

Abstract

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Full Text

Preamble

Astronomical Techniques and Instruments, Vol. 2, July 2025, 239–245

Article

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Suppression of electromagnetic crosstalk in kinetic inductance detector arrays by redesigning the pixel arrangement

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Received: November 30, 2024; **Accepted:** January 26, 2025; **Published Online:** May 16, 2025

https://doi.org/10.61977/ati2024066
https://cstr.cn/32083.14.ati2024066

Citation: Huang, H. C., Sun, S. L., Shi, X. D., et al. 2025. Suppression of electromagnetic crosstalk in kinetic inductance detector arrays by redesigning the pixel arrangement. *Astronomical Techniques and Instruments*, 2(4): 239−245. https://doi.org/10.61977/ati2024066.

Abstract

Superconducting kinetic inductance detectors (KIDs) are considered to be a highly promising technique for the large-scale imaging of millimeter and submillimeter waves in astronomy. As the pixel density and the array size increase, electromagnetic crosstalk inevitably becomes a problem that prevents increasing the multiplexing during the development of larger KIDs arrays. In this work, an effective method is introduced to suppress the electromagnetic crosstalk and achieve a compact pixel distribution and small frequency intervals. The electromagnetic crosstalk is first analyzed by simulating the behavior of two neighboring pixels, and the physical distance and the frequency interval are optimized. Then, the arrangement of the pixels on the whole array is redesigned using a genetic algorithm to satisfy the requirements. The simulation results reveal that the normalized electromagnetic crosstalk can be reduced to 0.5% on an 8 × 8 array. Larger arrays of 16 × 16 pixels have been fabricated and measured to validate this method, and the results reveal that both the resonance property and survival rate of pixels are improved effectively with this method. This method will be very helpful for designing high-multiplexing KIDs arrays within a limited bandwidth.

Keywords: Kinetic inductance detector; Crosstalk; Submillimeter wave; Resonator

1. INTRODUCTION

KIDs are considered to be one of the most promising techniques for millimeter and submillimeter wave imaging because of their inherent frequency division multiplexing ability, which makes it easier to fabricate large KIDs arrays [1,2]. KIDs were first proposed at Caltech and Jet Propulsion Laboratory (JPL) [3], and they have been developed rapidly in recent years. Some important projects based on KIDs have been subsequently proposed, such as the MUltiwavelength Sub/millimeter (MUSIC) Camera on the Caltech Submillimeter Observatory (CSO) telescope [4], New IRAM KID Arrays (NIKA) and NIKA2 on the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope [5,6], Microwave KIDs (MKIDs) on Balloon-borne Large Aperture Submillimeter Telescope (BLAST) The Next Generation (BLAST-TNG) [7,8], and an MKID on the Cerro Chajnantor Atacama Telescope-prime (CCAT-prime) [9,10]. The number of pixels on one array has grown from the initial dozens to thousands. With increases in pixel density, a substantial challenge for KIDs chips is unwanted electromagnetic crosstalk, which is caused by the electromagnetic coupling between neighboring resonators, complicating the readout imaging [11–13].

There are several methods for reducing the electromagnetic crosstalk before KID arrays are fabricated. Increasing the width or modifying the structure of the ground between neighboring pixels is one way to reduce electromagnetic crosstalk. Adane et al. optimized the structure of the ground by replacing it with a grid ground that reduced the crosstalk and kept the array more compact [14]. Increasing the frequency interval between neighboring pixels is another way to reduce electromagnetic crosstalk. Yates et al. presented a model of the crosstalk in KIDs and showed that it is a function of the frequency interval between neighboring pixels, which indicates that increasing the frequency interval between neighboring pixels can also reduce electromagnetic crosstalk [15]. Liu et al. and Shu et al. introduced a method called capacitor trimming to reset the resonant frequencies in an array by secondary processing, obtaining a highly uniform distribution of resonance points [16,17]. Mates et al. and Groh et al. revealed that the electromagnetic crosstalk is proportional to the mutual inductance between neighboring pixels, which is inversely proportional to the square of the frequency interval [18,19].

Electromagnetic crosstalk and pixel density parameters are in a trade-off relationship. Some research groups have proposed their own methods for reducing electromagnetic crosstalk during the fabrication of KIDs arrays, but they lack detailed and systematic descriptions for optimizing the design of the array given restrictions in the bandwidth, pixel density, and other factors. In this work, we introduce a method to suppress electromagnetic crosstalk by redesigning the pixel arrangement in an array. This method was first optimized using simulations, and then real KID arrays were fabricated and their performance measured to validate this method. The results indicate that the electromagnetic crosstalk was significantly suppressed after the rearrangement of the arrays.

2. SIMULATION

A lumped element resonator design that is similar to the KIDs arrays in NIKA2 was used in the simulation [5]. The size of the resonator (one pixel) in this design is about 0.7 mm × 0.7 mm, and consists of an interdigital capacitor and a meander inductor surrounded by the ground for isolation, as shown in Fig. 1 [Figure 1: see original paper]. The line width of the interdigital capacitor is 8 m, and that of the meander inductor is 4 m. The distance between the interdigital capacitor and ground is 50 m, and the distance from both sides of the inductor to the ground is also 50 m. The resonant frequency is adjusted by changing the length of the electrodes of the interdigital capacitor. The resonator array is read out by a coplanar waveguide (CPW) with center and gap widths of 20 and 12 m, respectively, which correspond to a characteristic impedance of 50 Ω. The width of the ground between the resonator and CPW is 20 m, which ensures a coupling quality factor of about 5×10^4. The width of the ground between two horizontally neighboring resonators is denoted as G, whereas the width of the ground between the CPW and vertically neighboring resonators is denoted as g. The simulation was performed using Sonnet software (release 18.58). In the model, the substrate is a 300 m-thick Si layer with a relative dielectric constant r = 11.9.

Fig. 1. Resonant frequencies with respect to the width of the ground between two neighboring resonators in (A) the horizontal direction and (B) the vertical direction.

Fig. 1A shows the frequencies of two horizontally neighboring resonators working together (f_1 and f_2 are the frequencies of Resonators 1 and 2, respectively) with respect to the width of the ground between them. The dashed line indicates their original resonant frequencies when they are simulated separately. The only difference between Resonator 1 and Resonator 2 is the difference in the length x of the interdigital capacitor electrodes. This difference, $\Delta x = 4$ m, is achieved by cutting one electrode of the interdigital capacitor, which causes a difference in the intrinsic resonant frequency of approximately 4 MHz. Both f_1 and f_2 deviate from their original values when the width of the ground is small, and return to their original value when the ground is wider than 400 m. It is obvious that the ground between the resonators has a shielding effect on the electromagnetic coupling between the resonators; that is, the wider the shielding ground, the stronger the shielding effect. Fig. 1B shows a similar trend for two vertically neighboring resonators, although the frequency change is smaller than that shown in Fig. 1A. The reason is that the magnetic field distribution differs in the horizontal and vertical directions. For this lumped element resonator, the inductance part is placed mainly along the vertical direction, and hence the magnetic field around the resonator extends mainly along the horizontal direction, and horizontally neighboring resonators suffer from higher levels of electromagnetic crosstalk as a result. The results of this simulation reveal that the ground widths G and g between resonators should be over 400 m to suppress the electromagnetic crosstalk. However, wider grounds lead to lower optical efficiency and pixel density.

The majority of the electromagnetic crosstalk comes from an effect called the coupling harmonic oscillator, which usually happens when neighboring resonators have close resonant frequencies [18]. Suppressing the crosstalk by enlarging the width of the ground between resonators alone is not an efficient solution, and the frequency interval between neighboring resonators also should be taken into account. Fig. 2A [Figure 2: see original paper] shows the plots of Δf versus Δf for different values of ground width G. Here, f_1 is the resonant frequency of Resonator 1 and f_2 is the resonant frequency of Resonator 2, which yields Δf = $f_2 - f_1$. Because of the influence of Resonator 2 on Resonator 1, f_1 shifts to f $_1$, giving a frequency shift of Δf = f $_1$ − f_1, and hence, Δf is used to represent the level of the electromagnetic crosstalk between the two resonators. This simulation clearly reveals that the electromagnetic crosstalk depends on both the value of ground width G and frequency interval Δf. When the value of ground width G is small, even if Δf is large, a frequency shift Δf still exists. When G is greater than 80 m, the situation becomes better, and the frequency shift gradually approaches 0 when Δf > 70 MHz, meaning that Resonator 2 has little influence on Resonator 1. Similar results can also be observed in Fig. 2B, which shows the results for two vertically neighboring resonators. Using the results of this simulation, the restrictions on both the width of the ground and the frequency interval can be determined during the design of an array.

Fig. 2. (A) Change in the frequency Δf of Resonator 1 versus frequency interval Δf for different values of ground width G. (B) Change in frequency Δf versus frequency interval Δf for different values of ground width g.

The simulation results of two neighboring resonators are not sufficient for determining the width of the ground because the phenomenon of electromagnetic crosstalk is highly complicated, especially for resonators operating under superconducting conditions with a large Q factor and high sensitivity. To investigate the detailed phenomenon of crosstalk on a whole array, simulations on 8 × 8 arrays were performed based on the simulation results for two neighboring resonators above. Here, we varied the horizontal ground width G and kept the vertical ground width g fixed. Two array arrangements were adopted, as shown in Fig. 3 [Figure 3: see original paper], where the resonators are numbered from 1 to 64, and each resonator has a unique resonant frequency. The resonators all have similar structures; the only difference is the length of the electrode of the capacitor. A change in electrode length of Δx = 4 m causes a change in resonant frequency of Δf_{design}   3.5 MHz. Resonator 1 has the lowest frequency, and Resonator 64 has the highest resonant frequency. The first array is sequentially arranged along the feedline, and the second has been rearranged by a genetic algorithm such that the real frequency intervals between neighboring resonators in the horizontal and vertical directions are at least 20Δf_{design}, which is about 70 MHz.

Fig. 3. Different pixel arrangements in the arrays. (A) Sequential arrangement along the feedline. (B) Rearrangement by a genetic algorithm.

Fig. 4A [Figure 4: see original paper] shows the simulated transmission characteristics (S_{21}) for arrays with different ground widths G and g before rearrangement. Each downward peak represents the resonant frequency of a resonator. For each 64-pixel array, 64 resonant frequencies can be observed. Theoretically, the resonant peaks in the frequency domain would be very evenly distributed if there were no electromagnetic cross coupling; however, the peak intervals vary. Some neighboring peaks nearly overlap while others are far apart. After increasing G and g, the distribution of the peaks becomes more uniform, but overlaps can still be found, and some of the resonant peaks are not strong enough. Fig. 4B shows the simulated S_{21} for arrays with different ground widths G and g after rearrangement using the genetic algorithm. A comparison with the results in Fig. 4A shows that, for the same ground widths, the resonance profile of the rearranged array is much more uniform than that of the sequential arrangement array.

The statistics of the frequency intervals are visualized in Fig. 4C and Fig. 4D. When the pixels are arranged sequentially, Δf varies from 0.5 MHz to 8 MHz, and some neighboring resonant frequencies are so close that they may result in the wrong response during array operation. The best standard deviation of Δf is 0.75 when G = 160 m and g = 100 m. After genetic algorithm-based rearrangement, Δf becomes much closer to its desired value, and the standard deviation is only 0.43 when G = 160 m and g = 100 m. Hence, by increasing the real frequency interval between two neighboring pixels, the crosstalk is suppressed, and a more uniform distribution of resonance points can be obtained. Parameter g has less influence on the distribution of resonant frequency, as the standard deviation of Δf does not substantially change when ground width g is further increased.

The simulation above indicates how an array with a uniform and compact distribution of resonance points can be obtained, which is very helpful in the design and fabrication of KID arrays. To validate the effectiveness of the rearrangement, a dynamic process was simulated. Assume that when one resonator in an array is illuminated, a frequency shift is generated in this resonator, and due to the crosstalk, an undesired frequency shift will also be generated in the neighboring resonators of the KID array. As shown in Fig. 5A [Figure 5: see original paper], one resonator (Resonator 28) in a 64-pixel array (G = 160 m; g = 100 m) was chosen, and its resonant frequency was intentionally slightly modified (~2 MHz) to imitate illumination. Next, the frequency shift of all the resonators was calculated before and after illumination. Fig. 6B [Figure 6: see original paper] and Fig. 6C show the shift in resonant frequency of the whole array before and after rearrangement. A clear difference is observed between the two arrays. In the sequential arrangement array, only Resonator 28 is illuminated, but frequency shifts appear in Resonators 25 to 30. The frequency shift is so large, the response of the array is unsuitable for imaging millimeter and submillimeter waves. In the rearranged array, when the light is illuminated on Resonator 28, only a very small frequency shift of 0.01 MHz is observed in two resonators, and this can be ignored because this error in the response is only 0.5%. This simulation result from the dynamic process indicates that the rearrangement of the array is very effective at suppressing electromagnetic crosstalk during imaging using KID arrays.

Fig. 5. (A) Dynamic process simulation. One resonator (Resonator 28) was used, and its resonant frequency was changed intentionally to imitate light illumination. (B) Frequency shifts of the sequential 64-pixel array. (C) Frequency shifts of the rearranged 64-pixel array.

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3. FABRICATION AND MEASURED RESULTS

To verify the solution described above, two 256-pixel KID arrays with different distributions were designed and fabricated. The first was arranged sequentially, and the other one was arranged using the genetic algorithm-designed configuration employed in the simulation. The ground widths G and g between pixels were 160 m and 100 m, respectively. The circuit of the resonators was deposited using Al magnetron sputtering on a single-crystal high-resistivity silicon substrate with a thickness of 50 ± 5 nm. The designed frequency interval was 2.5 MHz, and the Q factor was $\sim 5 \times 10^4$.

Fig. 6A shows the fabrication process of the 256-pixel KID arrays. First, a layer of photoresist was spin-coated on the cleaned silicon substrate for the following lithography step. Second, the circuit pattern on the mask was transferred to the photoresist through ultraviolet exposure. Third, the resonator circuit was deposited via Al RF sputtering with a thickness of 50 ± 5 nm. Lastly, the unwanted metal layer was removed by dissolving the photoresist, leaving the circuit structure on the substrate. The fabricated 256-pixel KID array and some enlarged parts are shown in Fig. 6B–Fig. 6D. The KID array was then mounted in a copper sample holder. To match the impedance, we used two CPW PCBs for the transition between the chip and the SMA connectors. The resonance property was measured by a network analyzer at 70 mK.

Fig. 6. (A) Fabrication process of the 256-pixel KID arrays. (B)–(C) Local enlarged parts of the array. (D) Image of the whole fabricated KID array. (E) The KID array mounted in a copper sample holder.

Fig. 7A [Figure 7: see original paper] shows the measured transmission characteristic curves for the KID arrays with different pixel arrangements. For the original array, 215 effective resonance points (84% survival rate) were observed, whereas 242 effective resonance points (95% survival rate) were observed in the rearranged array. The effective resonance points were obtained by fitting the resonance curve based on the equation in Gao's work [20]. The resonance properties of the array, such as the baseline and the depth of the resonant peaks, become more uniform after rearrangement. The statistics of the measured frequency intervals Δf are summarized in Fig. 7B and Fig. 7C. Frequency intervals Δf are closer to our desired value after rearrangement of the pixel arrangement. The standard deviation of Δf is 1.05 before rearrangement and 0.68 after rearrangement, indicating that the frequency shifts caused by the crosstalk are effectively suppressed. Frequency intervals Δf of over 5 MHz are not included in the standard deviation calculations because Δf of over 5 MHz is likely attributed to the absence of resonant peaks caused by fabrication failure, such as cracks in the circuit of the resonator, making it ineffective.

Fig. 7. (A) Measured resonance properties of the sequential and rearranged KID arrays. (B) Statistics of the frequency intervals for the sequential 256-pixel array. (C) Statistics of the frequency intervals for the rearranged 256-pixel array.

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4. CONCLUSION

In this work, an effective solution was introduced to demonstrate how electromagnetic crosstalk can be suppressed to achieve a high pixel density and narrow frequency intervals. The electromagnetic crosstalk was first analyzed by simulations to determine the necessary frequency intervals between neighboring resonators at a certain ground width, and then the arrangement of resonators on a whole array was redesigned using a genetic algorithm. Large arrays of 256 pixels were fabricated and measured to validate this solution. After rearrangement, the resonance properties and survival rates were substantially improved. The solution introduced in this work will be very helpful in the fabrication of large-scale, low-crosstalk KID chips. Although this method was developed using lumped element resonators, this concept could also be applied to resonators in other structures.

ACKNOWLEDGEMENT

This work is supported by the National Key Research and Development Program of China (2023YFC2206601), the National Natural Science Foundation of China (12273024, 62205211), and the Science and Technology Commission of Shanghai Municipality (23010503900, 22590780100). The author thanks the Millimeter and Submillimeter Wave Laboratory at Purple Mountain Observatory, Chinese Academy of Sciences, for the measurements of the KID arrays.

AI DISCLOSURE STATEMENT

AI-assisted technology is not used in the preparation of this work.

AUTHOR CONTRIBUTIONS

Houceng Huang conceived the ideas, implemented the study, and wrote the paper. Shilin Sun and Yaqian Zhang helped the simulation. Xiandong Shi contributed to the literature search. Yuechen Zhao revised the paper and improved quality of English. Weijie Du supervised the review process and provided guidance on the selection of topics and the interpretation of the literature. Dejun Liu reviewed and edited the manuscript, ensuring its academic rigor and clarity. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Note: Figure translations are in progress. See original paper for figures.
