Physical characteristics of delay-line current-biased kinetic inductance detector

*Yuki Iizawa¹, Hiroyuki Yamaguchi¹, Yuya Miki¹, Kazuma Nishimura, Hiroaki Shishido¹,², Kenji M. Kojima³,⁴, Kenichi Oikawa⁵, Masahide Harada⁵, Shigeyuki Miyajima²,⁶, Mutsumi Hidaka⁷, Takayuki Oku⁵, Kazuhiko Soyama⁵, Tomio Koyama⁸, and Takekazu Ishida¹,²

¹Department of Physics and Electronics, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan
²NanoSquare Research Institute, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan
³Muon Science Laboratory and Condensed Matter Research Center, Institute of Materials Structure Science, KEK, Tsukuba, Ibaraki 305-0801, Japan
⁴Department of Materials Structure Science, The Graduate University for Advanced Studies, Tsukuba, Ibaraki 305-0801, Japan
⁵Materials and Life Science Division, J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
⁶Advanced ICT Research Institute, NICT, Kobe, Hyogo 651-2492, Japan
⁷National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba
⁸Institute for Materials Research, Tohoku University, Sendai, Miyagi 980-8577, Japan

Abstract Our preceding works reported the development of a high spatial and temporal resolution imaging system by using a current biased kinetic inductance detector (CB-KID) with the use of a delay-line technique. We called this system as a delay-line CB-KID, and succeeded in imaging of neutron events caused by the nuclear reaction and hot spots produced by using the delay-line CB-KID system. It was essentially important for our proposal to use a superconducting stripline to guide the pulsed signal where the signal propagates at a constant fast velocity along the stripline. In the present study, we intend to measure a propagation velocity of the signal along the stripline precisely to compare with the theoretical prediction of the signal propagation, which was recently developed with a superconducting waveguide S-I-S model by Koyama and Ishida [11]. Our present measurements showed a good agreement between the theoretical predictions and the experimental results on the propagation velocity as a function of temperature.
1. Introduction

Neutron imaging has been very useful for both scientific research and various applications. For example, neutron diffraction can determine the atomic structure or magnetic structure of various interesting materials [1]. We can observe the dynamics of carbons and water molecules in fuel cells and so forth [2]. There are still strong demands to improve the specifications of neutron detectors. On the other hand, it has been known to date that various sorts of superconducting detectors have been quite successful compared to conventional detectors. For example, a transition edge sensor (TES) [3], a superconducting nanowire single photon detector (SNSPD) [4], and a microwave kinetic conductance detector (MKID) [5] are recognized to work quite excellently in the communities. Generally, it is well known that superconducting detectors have features of high sensitivity, fast response and high-energy resolution. We may say that it was not so often to utilize a superconducting detector in measuring neutrons.

Recently, a TES with a B neutron absorption layer was proposed to use as a neutron detector [6]. Our group also proposed a superconducting neutron detector for intending a high spatial and temporal resolution imaging system of neutrons using a current biased kinetic inductance detector (CB-KID) with a $^{10}$B neutron absorption layer [7,8,9] and the idea of a delay-line CB-KID technique [10]. A delay-line CB-KID is to use a signal transmission along the superconducting stripline as a delay line, where information on position can be derived from a difference in arrival timestamps. We need two conditions so as to obtain reliable positional data. One is to satisfy a constant propagation velocity for conducting imaging during the CB-KID measurements because the spatial resolution depends on the accuracy of the time and the propagation velocity. The other is to understand the physical basis of the delay-line CB-KID operation.

Recently, a theory of the signal propagation on a superconducting waveguide having an S-I-S structure has been proposed by Koyama and Ishida [11] within the framework of the London-Maxwell theory. The theory gave us a basis of operating mechanism of the CB-KID, and predicted a propagation velocity as a function of temperature. This model can be tested by the experiment. In the present work, for this purpose, we experimentally determined the signal propagation velocity along the CB-KID stripline as a function of temperature to test the validity of the Koyama-Ishida theory [11].

2. Current biased kinetic inductance detector

We briefly explain our CB-KID [7,8,9], which consists of a superconducting Nb ground plane, a superconducting Y meanderline of Nb wire, a superconducting X meanderline of Nb wire, and a $^{10}$B conversion layer from neutrons to charged particles. The nuclear reaction $^{10}$B(n, $^4$He)$^7$Li mainly emits a $^4$He particle of 1.47 MeV and a $^7$Li particle of 0.88 MeV, and the local energy dissipation to the meanderline provided by each projectile is used to create a hot spot on the Nb nanowire stripline. The signal is caused by the hot spot when the stripline is biased by the DC current while the hot spot is caused by the nuclear reaction
between a $^{10}$B nucleus and a single neutron.

The primitive explanation of the operating principle of the CB-KID is as follows. A meanderline is cooled down to a temperature lower than a transition temperature $T_c$ of the Nb wire. The inductance $L$ in superconducting meanderline is expressed as

$$ L = L_m + L_k + \Delta L_k , $$

where $L_m$ is the magnetic inductance, $L_k$ is the kinetic inductance but for a possible hot spot area, and $\Delta L_k$ is a tiny fraction of kinetic inductance from a region, where a hot spot will be created. The magnetic inductance $L_m$ is given by

$$ L_m = \frac{\mu \ell}{4 \pi} , $$

where $\mu$ is the magnetic permeability and $\ell$ is the total length of the stripline. The kinetic inductance $L_k$ is given by

$$ L_k = \frac{m_s \ell}{n_q S} , $$

where $m_s$ is the effective mass of the Cooper pair, $q_s$ is the electric charge of the Cooper pair, $n_s$ is the Cooper pair density, $\ell$ is the total length of stripline, and $S$ is the cross-sectional area of stripline. When some amount of energy is given to the superconducting meanderline, it produces a hot spot in a tiny fraction ($\Delta l \ll \ell$) of the meanderline. In the hot spot, the Cooper pairs are destroyed in a restricted regime of the stripline, and this induces a local change in the kinetic inductance ($\Delta L_k$) because the number of the Cooper pairs are instantaneously reduced in the limited region. If a DC-bias current flows through the entire meanderline, a transient change in the kinetic inductance causes a pair of voltage pulses, which propagate as a pair of electromagnetic waves propagating toward both ends of the Nb stripline with opposite polarities. A voltage pulsed signal $V(t)$ initially appears at the hot spot as expressed by

$$ V(t) = R I_b + \frac{d(L_m + L_k + \Delta L_k)I_b}{dt} \approx I_b \frac{d(\Delta L_k)}{dt} , $$

where the magnetic inductance $L_m$ does not alter with time because $L_m$ is described by the permeability as in equation (2), and the DC bias current does not change at all ($dI_b/dt \equiv 0$) as far as the detector is kept in the superconducting zero-resistance state. However, the sign of the local voltage signal depends on the direction of the bias current $I_b$ in equation (4).

In our previous work [7,8,9], we fabricated a neutron detector using Nb-based CB-KID coated with a $^{10}$B conversion layer. The reaction of $^{10}$B(n,$\alpha$)$^7$Li releases energy by 1.02 MeV or 0.84 MeV with a $^7$Li particle and by 1.78 MeV or 1.47 MeV with an $\alpha$ particle. The superconducting meanderline generates a pair of voltage signal pulses when the superfluid density changes by the nuclear reaction in a limited tiny segment.
3. Imaging from a quartet set of travelling signals from delay-line CB-KID

The delay-line CB-KID is able to image the distribution of hot spots on the detector. Since the present studies are related with the imaging capability of the CB-KID, we will explain the principle of imaging. Figure 1 (a) shows the Nb nanowire in CB-KID. One can see a clear image of the crossing area of the X and Y meanderlines. Both the X and Y meanderlines consist of 10000 stripline segments of 0.9-μm width, 15.1-mm length, and 0.6-μm spacing. The repetition period is 1.5μm and total length of meanderline reaches 151 m.

![Diagram](image)

**Figure 1.** (a) The photograph of the entire CB-KID device. We also show the laser-microscope photographs of the edge of Y meanderline, the edge of X meanderline, the crossing region of the X and Y meanderlines, and the region of the end electrode of X meanderline. We also list the fundamental parameters of our CB-KID. (b) Schematic view of a delay-line CB-KID imaging system. The positive signal goes to the upstream side of the bias current while the negative signal goes toward the downstream side.

Figure 1 (b) shows schematic view of our delay-line CB-KID imaging system. As we explained in section 2, a pair of voltage pulses with opposite polarities appear when a hot spot occurs in the meanderline and propagate as electromagnetic wave toward both ends along the Nb stripline. A negative pulse propagates along the same direction to the DC-bias current flow while a positive pulse propagates to the opposite direction. Both pulses propagate through meanderline and arrive at one of the ends of the meanderline. Both arrival times at the ends of meander are different from each other depending on the travelling lengths of the two signals. We call this deferent time as a delay time Δt. In case of figure 1 (b), an arrival time of positive pulse is \( t_1 \), an arrival time of negative pulse is \( t_2 \), and a delay-time \( Δt \)
is $t_1 - t_2$. We can calculate a position from a delay time $\Delta t$ and a propagation velocity $v$. A hot spot position in the meanderline can be determined as follows:

$$x = \text{ceil}\left\{\frac{\Delta t}{2hv}\right\}p,$$

where $h$ is the length of each segment of the meanderline, $p$ is a repetition pitch for the meanderline. The “ceil” is a ceiling function, which works to convert the signal propagation length to the number of segments required for signal traveling. The $Y$ position also can be determined in a similar manner, and hence we can image the positions of the mesoscopic excitations in the two-dimensional plane by using the very limited number (four) of leads for the readout circuits.

According to equation (5), we recognize that the propagation velocity $v$ of the meanderline is directly relevant to the accuracy of the $X$ positon obtained in our method. Therefore, it is very important to know the propagation velocity as precisely as possible. In addition, we have to understand the physical mechanism of the signal generation and transmission in CB-KID.

4. S-I-S structure of delay-line CB-KID and propagation velocity

Recently, Koyama and Ishida gave a theory of the signal generation and the propagation in CB-KID, and will be reported elsewhere [11]. We briefly summarize an essence of the theory to compare with the present experimental results.

A delay-line CB-KID consists of a superconducting Nb meanderline layer, a SiO$_2$ insulator layer, and a superconducting Nb ground plane layer. According to this configuration, the signal transmission is very efficient along the stripline due to the impedance matching in superconducting circuit. The schematic modelling view of a part of the stripline in our delay-line CB-KID is depicted in Figure 2. We regard this stripline as an S-I-S waveguide structure. On the basis of this modelling, Koyama and Ishida treated the system to obtain the signal generation and propagation on the basis of the London-Maxwell theory, and obtained an analytic formula of propagation velocity as a function of temperature [11]. The CB-KID is modeled as a structure of S-I-S while no tunneling currents are flowing due to a thicker layer of the insulator. Therefore, the system is very different from the Josephson junction (JJ) where the Cooper
pairs tunneling is important, but it is useful to treat the dynamics of the system in terms of a superconducting phase difference as in JJ. The gauge-invariant phase difference $\theta(x, t)$ between the stripline and the ground plane is defined by

$$
\theta(x, t) = \varphi(x, d, t) - \varphi(x, -\infty, t) - \frac{e^*}{\hbar c} \int_{-\infty}^{d} dz A_x(x, z, t),
$$

(6)

where $\varphi(x, z, t)$ is the superconducting phase at $(x, z, t)$, $A_x(x, z, t)$ is the $z$ component of the vector potential, $d$ is a thicknesses of insulating and superconducting layers and $e^* = 2e$ is the charge of a Cooper pair. $\theta(x, t)$ is the gauge-invariant phase difference between a point on the lower surface of the superconducting wire ($z = d$) and a point at a deep inside the superconducting ground plane. Following a procedure, which is often used in the theory of Josephson effect, one can drive the equation of motion for $\theta(x, t)$ as follows:

$$
\frac{\lambda_L + d}{d^2} \frac{1}{c^2} \frac{\partial^2 \theta(x, t)}{\partial t^2} - \frac{\partial^2 \theta(x, t)}{\partial x^2} = \frac{e^*}{\hbar c} \frac{\partial}{\partial x} \left[ A_x(x, d, t) - \frac{\hbar c}{e^*} \frac{\partial \varphi(x, d, t)}{\partial x} \right]
$$

(7)

where the right-hand-side term of equation (7), $\frac{\partial}{\partial x} \left[ A_x(x, d, t) - \frac{\hbar c}{e^*} \frac{\partial \varphi(x, d, t)}{\partial x} \right]$, arises from the current flowing in the lower surface of the superconducting nanowire. Using the London equation and the Maxwell equations, they obtained the wave equation from equation (7) as follows:

$$
\frac{1}{v^2} \frac{\partial^2 \theta(x, t)}{\partial t^2} - \frac{\partial^2 \theta(x, t)}{\partial x^2} = 0
$$

(8)

where the velocity $v$ is given as

$$
v = \frac{c}{\sqrt{\varepsilon}} \sqrt{\frac{d}{d+\lambda_L \left(1+\coth(s/\lambda_L)\right)}}
$$

(9)

where $c$ is the speed of light in a vacuum, $\varepsilon$ is the dielectric constant of insulating layer, $s$ is the thickness of superconducting nanowire and $\lambda_L$ is the London penetration depth. Note that the velocity $v$ is a function of the London penetration depth $\lambda_L$, which is dependent on temperature. Therefore, the propagating velocity $v$ is expected to vary with temperature. Assuming a typical BCS superconductor, we consider that the London penetration depth $\lambda_L$ approximately obeys the temperature dependence of the two-fluid model as follows:

$$
\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1-(T/T_c)^4}}
$$

(10)

where $T_c$ is a transition temperature. Note that equation (9) is different from the naïve prediction of the velocity in the stripline as
where $L_k^0$ is the unit-length kinetic inductance and $C_s$ is the unit-length capacity of the microstripline. Therefore, the precise experiment to determine the propagation velocity is necessary to provide the detailed data to compare.

5. Experimental apparatus to evaluate propagation velocity

5.1 Measurement system of propagation velocity

We plan to conduct systematic measurements of the propagation velocity to examine the validity of the London-Maxwell equation of the CB-KID [11]. Figure 3 shows the schematic view of measurement system of propagation velocity. Because our detector operates only at temperatures lower than $T_c$, CB-KID was cooled down by using a Gifford-McMahon (GM) cryocooler. A Cernox thermometer was placed in the neighborhood of the detector. The detector temperature was controlled by using a temperature controller, and was monitored the temperature and its stability through a GP-IB interface with the aid of a personal computer. We need a pulse signal of a narrow width to measure the propagation velocity precisely. For this purpose, we used a passive differentiation circuit to generate a sharp pulse from a rectangular wave of moderate width. The doublet pulse with a positive polarity and a negative polarity were generated by this method. We use a signal splitter to feed the pulses simultaneously to the X-meanderine as well as to the Y-meanderine. This signal is also fed into a Nb short wire on the same chip of CB-KID. The third signal is measured to compensate a lag time when the signal propagates along the semi-rigid cables wired inside of the cryostat, where all the semi-rigid cables were installed so as to have the same length. The output signals after transmitting the meanderline of CB-KID were amplified by the identical low-noise amplifiers located at room temperature. The gain of amplifier was nominally 46 dB with the bandwidth from 1 kHz to 100 MHz. The output signal amplified by the preamplifier goes to a digital oscilloscope with a 0.4-ns sampling period, and the whole signals were stored in the storage hard disk of the computer. A time difference between the signal passed through meanderine and the signal passed through the reference Nb short nanowire is determined by the post data analysis. Note that this method reasonably compensates a possible systematic error coming from a time in propagating the semi-rigid cable in the

\[
v = \sqrt{\frac{1}{L_k^0 C_s}}.
\]
cryostat. The propagation velocity was thus obtained from a time difference and the total length of the meander line.

### 5.2 Experimental results of propagation velocity

Figure 4 shows results of propagation velocity measurements and data points are fitted by the theoretical equations (9) by assuming the two-fluid model of equation (10).

![Figure 4](image)

**Figure 4.** Propagation velocity as a function of temperature. The data points are fitted well by the least-squares method to the formula (9) of the Koyama-Ishida theory [11]. We list the parameters used in the least-squares fitting as the fixed parameters ($c = 2.99792458 \times 10^8$ m/s, $d_x = 350$ nm, $d_y = 300$ nm, $s = 40$ nm) and the fitting parameters ($T_c = 8.7643 \pm 0.0007$ K, $\lambda(0) = 2.6366 \pm 0.00147 \times 10^{-7}$ m, $\epsilon = 2.8271 \pm 0.0261$ for the X detector, $T_c = 8.6799 \pm 0.0008$ K, $\lambda(0) = 3.00241 \pm 0.00241 \times 10^{-7}$ m, $\epsilon = 2.31159 \pm 0.0323$ for the Y detector.)

In the least squares method, the speed of light in vacuum $c$, the thickness of the insulating layer $d$, and the thickness of the superconducting nanowire $s$ were taken from the design parameters, the transition temperature $T_c$, the London penetration depth $\lambda(0)$ at 0 K, and the dielectric constant $\epsilon$ of insulating layer were taken as fitting parameters. We find that the propagation velocity depends on temperature. The experimental data obtained by the propagation velocity measurements were fitted quite nicely as predicted by Koyama and Ishida [11]. The agreement is much better than the prediction of equation (11). Parameters to fit the data are listed in Figure 4. We conclude that the London-Maxwell theory developed by Koyama and Ishida provides sound explanations of the operation principle of our CB-KID.
We notice that Zhao et al. [12] reported on delay-line imaging for single photon detector. Their system has a length of 19.7 mm and the signal propagates at a 2% speed of light velocity, which are in marked contrast with our work. Our system extend to 151 m more than 7500 times longer than their stripline, and the signal propagates at a 20%- of light velocity. Our system needs a fabrication technique enough to obtain a reliable device. Fast propagation velocity is also related with achieving a high-speed electronics in the future. Besides, our system works at the superconducting state while their system was supposed to be relevant to the resistive transient change in producing the system s. We have the double layers of the X detector and the Y detector employed in the present study. This is an essential difference from the method of Zhao et al. [12], and is inevitable to achieve a higher spatial resolution.

Further studies are in progress to investigate the bias current dependence of the propagation velocity to understand the operating mechanism. We consider that the CB-KID operation would be closely related with the operating principle of the superconducting nanowire single photon detector (SNSPD).

6. Conclusion

Our group previously proposed the idea of two-dimensional superconducting imaging method on the basis of the delay-line CB-KID method. It is characteristic of the method that works at high spatial resolution and high temporal resolution by using only the four-channel readout circuits. We emphasize that our system is extremely simpler than any other superconducting imagers. Koyama and Ishida [10] developed a theory based on the London-Maxwell theory, which gives not only the wave propagation equation but also the temperature dependence of the propagation velocity. In order to verify the theoretical validity of the Koyama-Ishida model, we carried out systematic measurements of the propagation velocity in the present work. Our results showed that the propagation velocity determined experimentally gives excellent agreement with the theoretical predictions by the London-Maxwell theory. We conclude that the Koyama-Ishida model [11] gives sound confirmation of the operating principle of the CB-KID mechanism.

Acknowledgement

This work is supported by Grant-in-Aid for Scientific Research (S) No. 23226019, and Grant-in-Aid (A) No.16H02450 from JSPS. The devices were fabricated in the clean room for analog-digital superconductivity (CRAVITY). This work is partially benefitted by the use of VDEC, the University of Tokyo with the collaboration with Cadence Corporation. This work is supported of MLF program (Proposal No. 2015A0129, No. 2015P0301).

References

[1] Rodríguez-Carvajal M J 1993 Physica B: Phys. of Condensed Matter 192, 55
[2] Bellows R J, Lin M Y, Arif M, Thompson A K, and Jacobson D 1999 *Journal of The Electrochemical Society* **146**, 1099

[3] Chervenak J A, Irwin K D, Grossman N G, Martinis J M, Reintsema C D, and Huber M E 1999 *Appl. Phys. Lett.* **74**, 4043

[4] Miki S, Yamashita T, Fujiwara M, Sasaki M, and Wang Z 2010 *Optics Letters*, **35**, 2133

[5] Mazin B A, Day P K, Zmuidzinas J, Leduc H G 2002 *AIP Conf. Proc.* **1**, 309

[6] Merlo V, Salvato M, Cirillo M, Lucci M, Ottaviani I, Scherillo A, Celentano G, and Pietropaolo A 2015 *Appl. Phys. Lett.* **106**, 113502

[7] Ishida T, Nishikawa M, Fujita Y, Okayasu S, Katagiri M, Satoh K, Yotsuya T, Shimakage H, Miki S, Wang Z, Machida M, Kano T, and Kato M 2008 *J. Low Temp. Phys.* **151**, 1074

[8] Yoshioka N, Yagi I, Shishido H, Yotsuya T, Miyajima S, Fujimaki A, Miki S, Wang Z, and Ishida T 2013 *IEEE Trans. App. Supercond.* **23**, Art. ID. 2400604

[9] Shishido H, Miyajima S, Narukami Y, Oikawa K, Harada M, Oku T, Arai M, Hidaka M, Fujimaki A, and Ishida T. 2015 *Appl. Phys. Lett.* **107**, 232601

[10] Shishido H, Miki Y, Yamaguchi H, Iizawa Y, Kojima K M, Oikawa K, Harada M, Oku T, Soyama K, Miyajima S, Hidaka M, and Ishida T 2017, 17th international workshop on Low Temperature Detectors (LTD17) July 16-21, 2017, Kurume, Japan

[11] Koyama T and Ishida T, this conference, to be published

[12] Zhao Q Y, Zhu D, Calandri N, Dane A E, McCaughan A N, Bellei F, Wang H-Z, Santavicca D F and Berggren K K 2017 *Nature Photonics* **11**, 247-251